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EDGAR
Evaluation and Decision Process for Greener Asphalt Roads

Energy efficient materials and technologies and their impact on sustainability

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Executive summary

This deliverable presents a review of the knowledge and information related to the sustainability of a wide range of materials and technologies, which are used for the production of bituminous mixtures.

NRA's may consider using these materials and technologies for several reasons, often for energy efficiency and environmental reasons, but also for social or economic reasons. The aim of the EDGAR project is to develop methodologies for the assessment of the overall sustainability of bituminous mixtures produced with these materials and technologies.

To develop such methodologies, it is essential to have a clear overview of the present day knowledge on these materials and technologies and specifically on their impact on the main sustainability criteria (environmental, social and economic).

The following materials and technologies are considered in the report:

- Technologies to reduce the production temperature compared to hot mix asphalt
- Cold or semi-cold production technologies
- The use of reclaimed asphalt
- The use of materials from secondary sources (other than reclaimed asphalt)
- The use of modified or alternative binders
- The use of various types of additives for various purposes

For each of these technologies, a brief description is given before discussing the impact on the main categories of sustainability criteria: global warming potential, use of energy and material resources, air pollution, recyclability at the end of life, health and safety and financial implications. The impact on performance is also discussed, because of the importance of the expected lifetime and maintenance when sustainabilty is assessed over the full life cycle.

Most of these technologies have been in use for many years, so a lot of information is already available on the technology itself and on the impact on the performance of the asphalt. Since it was not the aim to produce an exhaustive literature review on these topics, reference is often made to other reports or papers for more detailed information. Sustainability information however is not always available or very scarce, which implies that some sections of the review report remain with little or no information.

The review thus focuses not only on what is known, but also on the knowledge gaps that need to be filled in order to improve the sustainability assessment. Attention is also drawn to the risks or problems ("alerts") that may have an adverse impact. This highlights the needs for future research and draws the attention of the reader to some important issues that are frequently overlooked.

The report forms a basis for the future work planned in the EDGAR project. It shows the type of information the methodology can build upon, as well as the missing information, and will help in the selection of the most interesting test cases.

1 Introduction

1.1 Context

The EDGAR project aims at developing methodologies for the sustainability assessment of "green bituminous mixtures". "Green bituminous mixtures" is used in the context of this project as a general term for all types of bituminous mixtures in which specific materials or technologies are used with the aim of reducing the environmental impact. Paragraph 1.3 will expand on the various types of materials and technologies considered.

The project output is mainly intended for road authorities, who have to make the important decisions of allowing or refusing the use of particular materials and technologies in the production of bituminous mixtures.

Reduction of energy and CO_2 emissions are important motives for implementing new materials and technologies, but the quantification of these two parameters is not sufficient to demonstrate the viability:

- There are other environmental impacts to be considered, as described in the European norm EN 15804, which defines core rules for preparing Environmental product declarations for construction products. In the particular case of asphalt, the use of non-renewable resources is also known to have an important environmental impact.
- Road authorities have to balance environmental considerations against social and economic considerations, as the safety and wellbeing of road workers, road users and residents is crucial and the financial means are limited.
- A long term vision requires the consideration of the environmental, social and economic impacts from a life cycle perspective, including all stages from cradle to grave and the benefits and loads beyond the end of life (EOL). Such a long term perspective is only possible when the performance of the bituminous mixture is known and the expected lifetime can be estimated with sufficient confidence.

It is clear that the methodology for evaluating green asphalt mixtures has to be based on the principles of LCA, considering environmental, social and economic impacts.

Task 1.2 of the EDGAR project consists of reviewing the situation and experience with green materials and technologies applicable to bituminous mixtures and to summarize the information and data relevant to the sustainability assessment according to the most important assessment criteria. This report is the output of this task.

1.2 Aim and structure of the report

The aim of this report is:

1. *To provide a general overview of available information on green bituminous mixtures, with respect to the most important sustainability criteria.* This information is retrieved from literature (preferably from state-of-the-art reports and output of previous projects) and pre-existing knowledge residing within the project team.
2. To make a critical evaluation of the available information and to identify gaps in the existing knowledge.

3. *To detect "alerts" in the sustainability assessment of a given material or technology*. These are issues that could possibly jeopardize the overall sustainability and which therefore require particular attention from the road owner.

In order to collect and present the information in a comprehensive and structured way, the following approach was followed:

- On one hand, a selection was made of the materials and technologies to be considered in the review process. Paragraph 1.3 explains how this selection was made and how the selected materials and technologies were divided into categories.
- On the other hand, a selection was made of the sustainability criteria, which were considered the most relevant for bituminous mixtures at the beginning of the project. The process leading to this selection is explained in paragraph 1.4.

Subsequently, the report is structured per category of materials/technologies, and for each of the categories, the impact on the selected sustainability criteria is discussed.

1.3 Selection of materials and technologies

The selection of materials and technologies considered in this report was mainly based on the knowledge of the project team. The different members have been involved in various projects regarding these materials and technologies and therefore have experience with production, performance testing, field trials and in some cases even long term performance on the road.

The selection was limited to those techniques that are already in a sufficiently advanced stage of development, which means that they are already offered to road administrations and other clients at this date.

The EDGAR project focuses on the product "asphalt". Therefore, only those materials and technologies that intervene in the production of asphalt mixtures were considered. A product such as a stress relieving interlayer is outside the scope, although it could be considered as a green technology due to the extension of the lifetime of the overlay.

Table 1-1 shows the six categories of materials and technologies discussed in this report. As already stated, this list is a selection made by the project team and is therefore not to be considered as an exhaustive list.

It was a well-considered choice of the project team to group the materials and technologies in generic categories and not to consider individual products from particular companies or suppliers. The reason is that proposed methodologies should be generally applicable and not tailored to a specific product or technology. The situation is also that new products emerge regularly on the market, while others are being retrieved. That is why the project team decided to keep a list of products, suppliers and companies for private use within the project, but this list can not be exhaustive and up-to-date at all times.

Table 1-1: Selected materials and technologies

Warm mix asphalt	Foaming techniques Techniques using organic additives Techniques using chemical additives
Cold and semi-cold asphalt technologies	Emulsion based techniques Foam based techniques
Asphalt recycling	Plant recycling In situ recycling
Secondary materials	Steel slag Fly ash Crumb rubber Shredded roofing Crushed glass
Modified and Alternative binders	Vegetal or bio-binders Sulphur modified/extended bitumen Polymer modified bitumen
Additives	Anti-stripping agents Pigments for coloured asphalt Fibres Rejuvenators

1.4 Selection of sustainability criteria

An in-depth discussion of the sustainability criteria for green bituminous mixtures is foreseen in work package 2 of the project. In this paragraph, a simplified preliminary list is drawn to assist in the literature review. This list does not claim to be complete, detailed and accurate, but in general lines, it should cover the more detailed list that will follow in deliverable D2.1 of work package 2.

In a first step, a long list of sustainability criteria, which are generally applicable to roads, was drawn (see annex 1 for the complete list). This list is based on EN 15804, which describes the parameters required for the environmental assessment of construction products, and was further completed by social and economic criteria, with a focus on road construction. The list was considered for each of the different stages of the life cycle of an asphalt road. These stages are shown in **Table 1-2**, along with the main processes taking place in each stage.

Table 1-2: Life cycle stages and associated processes (for road pavements)

Production	Construction	Use	End of life (and beyond)
Raw material supply Transport of raw material to the production site Product manufacturing	Transport to the construction site Construction	Use Maintenance Repair	Demolition Transport Waste processing Disposal Recycling

In a second step, the list was evaluated specifically for the case of green bituminous mixtures. Some criteria, like ozone depletion, are not expected to be susceptible to the use of green materials and technologies and were therefore withdrawn from the list. Other criteria were combined:

- The creation of smog, fine particles, NO_x, SO_2, CO etc. was combined in *Air pollution*.
- Ecotoxicity was considered as a component of *Health and safety*.
- Noise and vibrations have an adverse effect on human health and were therefore also considered as part of *Health and safety*.
- All financial criteria were combined in one criterion called *Financial cost*.
- In the end-of-life stage, the bituminous material is reclaimed for recycling purposes. Not only the amount of recycled material is important, but also the quality has to be considered, since downcycling or incompatibility with new materials impede on the recycling potential. All these aspects have been combined in the criterion *Recyclability.*

Although the impact on health and safety of green bitumionous mixtures is discussed for a wide variety of techniques and materials reviewed in this report (also from outside EU), authors wish to draw attention to European legislation already in place (since 2007) covering worker health and chemical safety. REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) is a regulation of the European Union adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. REACH places the burden of proof on companies or suppliers. To comply with the regulation, companies must identify and manage the risks linked to the substances they manufacture and market in the EU. They have to demonstrate to the European Chemical Agency (ECHA) how the substance can be safely used, and they must communicate the risk management measures to the users. If the risks cannot be managed, authorities can restrict the use of substances in different ways. Consequently, the most hazardous substances should be substituted in the long run with less dangerous ones.

Finally the criterion *Performance* was added. This is an essential criterion, because of its impact on the lifetime of the pavement. Reduction of the lifetime will increase global warming, use of resources and financial costs, when these criteria are considered in a lifecycle perspective.

In the end, a more manageable list of specific criteria for the evaluation of any green material and technology for asphalt was obtained. This list is shown in **Table 1-3**, along with the stages of the life cycle to which each criterion applies. It was used for conducting the review process for this deliverable D1.1, as described in the following paragraph 1.5.

The risk or uncertainty inherent to the use of new materials or innovative technologies is not considered as a sustainability criterion. Nevertheless risk and uncertainty will play a role in the decision process as it will have an impact on the confidence in the sustainability assessment of a material or technique. Therefore it is important to also take risk and uncertainty information into account in the decision process.

Table 1-3: Selected sustainability criteria

	Production	Construction	Use	EOL
Global warming potential	x	x	x	x
Use of resources for energy	x	x	x	x
Use of resources for materials	x			
Air pollution	x	x	x	x
Health and safety	x	x	x	x
Financial cost	x	x	x	x
Recyclability	x			x
Performance		x	x	

1.5 Methodology

Based on the selections described in the previous paragraphs, the gathered information was categorized per type of material and technology (**Table 1-1**) and per sustainability criterion (**Table 1-3**).

Therefore, a large matrix was constructed in which the rows were formed by the selected materials and technologies, and the columns by the selected sustainability criteria in the different life cycle stages. The members of the project team could then enter the references to the relevant information in the appropriate matrix cells. This matrix not only facilitated the writing of this report, it also showed in the course of the reviewing process for which items a lot of information was available and where information was scarce or missing. In this way, the search for information could focus more specifically on the missing parts and, in case no information was found, identify the knowledge gaps.

Figure 1-1 shows a condensed version of this matrix, in which the bars represent the number of references that contained information for the cell. This representation gives a general impression of which topics are well discussed in literature and on which topics little or no information is available.

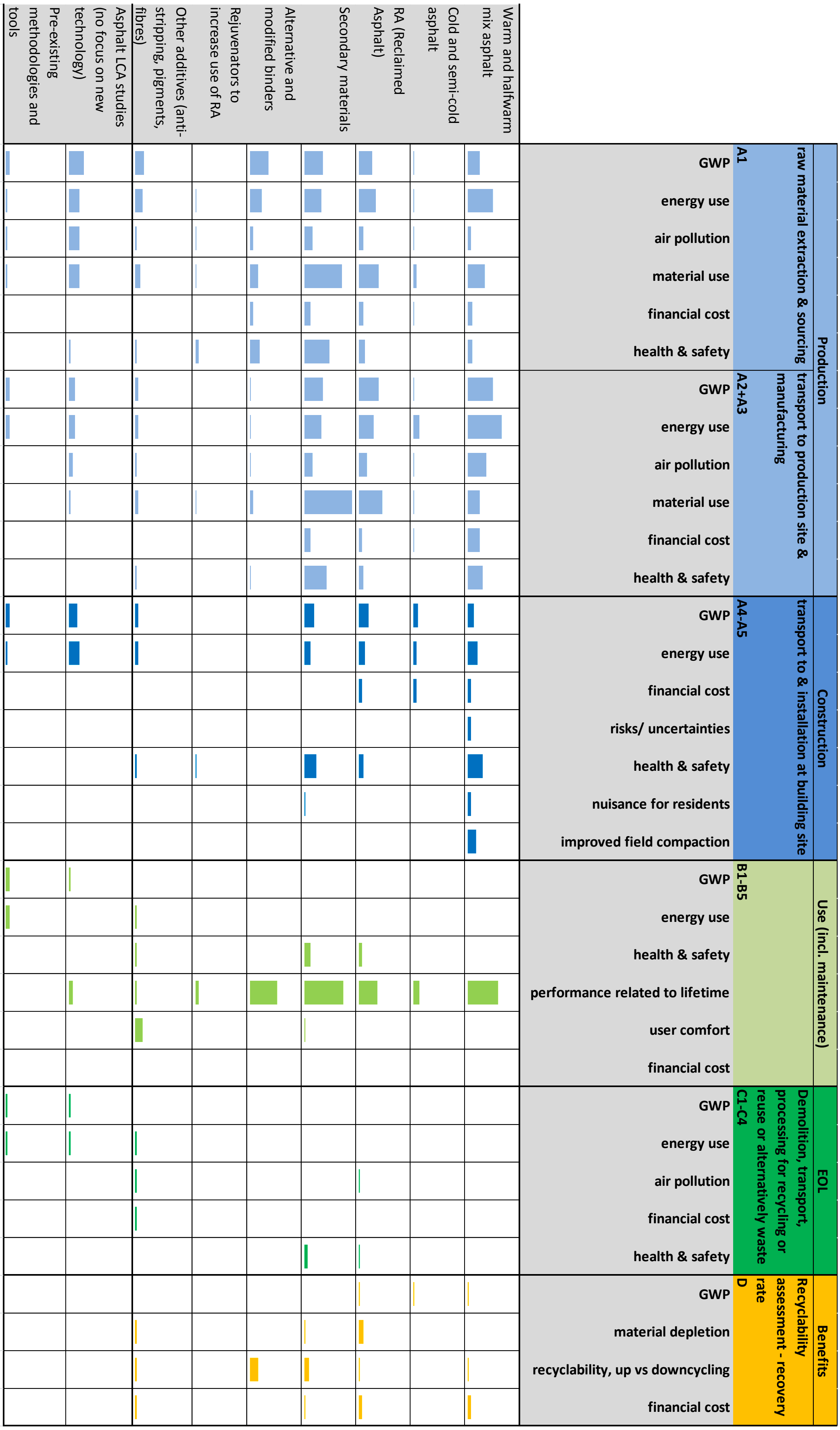


Figure 1-1: Schematic representation of the number of references dealing with the various topics (for the references used in this review report)

2 Warm and half-warm mix asphalt technologies

2.1 Introduction

While traditional hot mix asphalt (HMA) is produced at around 150-180 °C, warm mix asphalt (WMA) production consists in producing an asphalt mixture at a temperature below 140°C. This temperature reduction permits to save energy and, if produced in optimized conditions, decrease the air emissions as well. Some technologies even permit to reduce the production temperature below 100 °C. Asphalt produced at temperatures below 100-110 °C is conventionally called half warm mix asphalt (HWMA).

Figure 2-1 gives an estimation of the reduction in CO_2 emissions and fuel consumption that can be achieved in the production stage. The savings are highly dependent on the technology applied and on the local conditions (plant type, energy source, weather conditions, recipe, quantity produced, …), but one can estimate fuel savings of at least 1 l/t for warm mix asphalt and 1.5-3 l/t for half-warm mix asphalt.

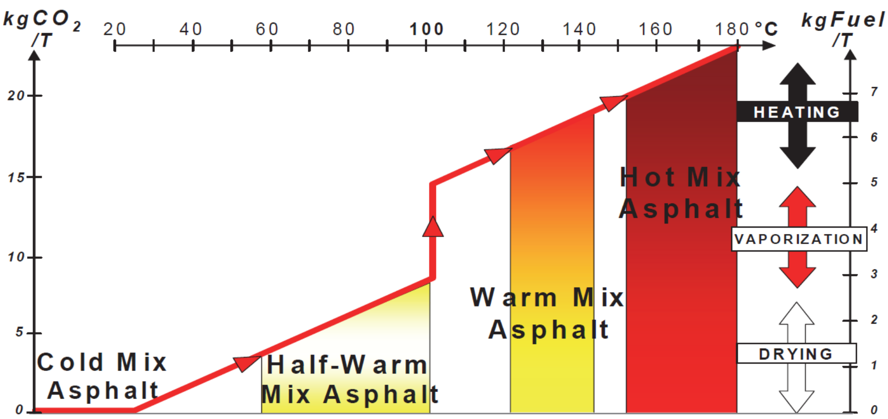


Figure 2-1: Global comparison between hot, warm and cold mix asphalt
(from Olard 2008)

As mentioned above, the basic idea consists in decreasing the production and laying temperature of the asphalt mixture. In order to achieve this, it is crucial to decrease the mixture viscosity in the production and laying temperature domain, this in order to guarantee a sufficient workability of the mixture. Various technologies (or processes) can be applied in order to decrease the mixture viscosity. These technologies can be divided into following categories:

- Foaming techniques
- Use or organic additives
- Use of chemical additives

For more detailed information related to the description of WMA and HWMA techniques, historical development and mechanical performance, one can refer to (D'Angelo & Harm 2008) and (Bueche 2011).

In this chapter warm mix asphalt techniques are reviewed in terms of the selected sustainability criteria set out in Table 1.3. Several publications related to WMA and HWMA sustainability aspects can be found. The present review does not aim at being exhaustive but should give a present-day view of the situation and available knowledge.

In the following paragraphs, a review of the literature ordered by sustainability criteria is provided. This review focuses on so-called ‘alerts’, either mentioned by the literature sources cited, or based on the reviewer’s knowledge and viewpoint. In paragraphs 2.2 to 2.4, the three categories of technologies are considered one by one, while in paragraph 2.5, additional literature sources are reviewed which consider and compare different categories of WMA and HWMA technologies.

2.2 Foaming techniques

2.2.1 Description

Foaming techniques are techniques requiring bitumen foaming. Bitumen foaming increases the volume and workability of the binder during a limited period of time and thereby allows to reduce the mixing and compaction temperature of the bituminous mixture. Foaming should be effective during the production and laying phase, but should not have any adverse effect on the final mixture performance.

Note that the concept is not completely new as the first experiments have been conducted in 1957 by Dr. Ladis H. Csanyi (Prof. Iowa State University). At that time, the purpose of the project was not WMA, but the use of foamed bitumen as a binder for soil stabilisation. Some WMA applications of foaming techniques have been reported in 1996 (Shell, Kolo Veidekke).

Bitumen foaming requires the addition of water. As the volume expansion is temporary, it is essential that the contact between the water and the binder is established just before asphalt mixing. Various methods can be applied in order to introduce the water in the asphalt mixture:

- Addition of zeolites (crystalline hydrated aluminium silicates containing crystalline water)
- Direct water injection into the bitumen
- Management of the aggregates humidity (moisture control)

Zeolites have been widely used in asphalt for many years, especially in Europe. Some applications date back to 1995 in Germany (Mitteldeutsche Hartseinindustrie AG, Eurovia) (Bueche 2011). The technique requires no major modifications to the production plant and process, but the cost of the additive is relatively important and the needed quantities might not be negligible.

Direct water injection into the bitumen requires the installation of a foaming unit, which is an important investment. Various types of foaming units exist, the difference being in particular in the nozzle configuration, the ability to clean the foaming unit, and the water injection conditions (pressure). All of these parameters have an impact on the volume expansion and the time stability, which are the most important characteristics of the foam.

Moisture control techniques seem promising, since these techniques do not require major modifications to the plant equipment or any special additives that would imply additional costs. The principle is based on the management of the inherent humidity of the aggregates.

However, this humidity management requires a control procedure and a water injection system that can be used in case of non-sufficient water content in the aggregates. One should also emphasize that the application of foaming technology using residual water/water injection requires a lot of experience, this in order to guarantee proper production in the plant and satisfactory asphalt mixtures properties. Besides, important differences can be found when comparing the processes. These will also impact the future mechanical performance of the asphalt pavement. Nevertheless, as water is considered as “free” by the plant owners (not considering additives or investment costs), these foaming techniques are being more and more used in recent years.

Numerous foaming technologies have been and are being developed by a variety of companies. A list of the existing technologies is kept by the project team for use in the project. The list has to be continuously updated because of the rapid evolutions in know-how and innovations in this domain.

2.2.2 Impact on sustainability criteria

Global warming potential

An extensive emission measurement campaign was performed by (Lecomte & al 2008) for WMA produced using a foaming technique (WAM-Foam® WMA). The results show a drastic reduction in GHG emissions in the production stage. Indeed, CO_2 emissions were about 35% lower for than for the reference hot mix asphalt.

In (Ventura & al 2009), the authors presented an experience related to LCA of a half-warm mix process (LEA®) through measurements at the asphalt plant and at the roadwork site. The authors reported a substantial decrease in CO_2 (factor 2.8). The calculation of some specific environmental indicators (GWP, energy equivalent EE and Photochemical Ozone Creation Potential POCP) for different life cycle stages (asphalt mixing, transport and paving) illustrated in particular the very important contribution of the asphalt mixing plant to the total impact and the better environmental performance of the HWMA in comparison with the reference HMA mixture (**Figure 2-2**).

(Hassan 2009) made a LCA of the WAM-Foam® technique in comparison to a conventional HMA. In order to achieve this, a LCI had first been conducted and BEES 4.0 (Building for Environmental and Economic Sustainability) was then applied for the calculation of various environmental factors such as global warming, fossil fuel depletion, air pollutants, smog formation and ecological toxicity. The system boundaries for the LCI were fixed by the author from asphalt binder and aggregate production, up to asphalt mixture placement. The results indicate that, covering all these stages, GWP decreased by approximately 4 % in comparison with the reference mixture, but air pollution decreased by as much as 24 %.

In (Van de Ven et al. 2012), the authors performed an extensive life cycle analysis of the half-warm process LEAB® (foamed bitumen mixture produced at approximately 100 °C or below). The study highlighted that the dominant environmental impacts over the life cycle are due to production at the asphalt plant, bitumen production, foreign aggregates extraction and transport and transport of RA to the plant. The study also indicated that the environmental performance (12 impact categories including global warming, ozone layer depletion, human ecotoxicity and energy) of mixtures that contain RA improves significantly, despite the increase in the energy use in the asphalt plant. The same authors also conducted a comparison between LEAB® and a conventional base course in the Netherlands. The environmental cost indicator ECI (environmental effects conversion into Euros) of LEAB® is approximately 25 % better than the indicator for HMA. The study concludes that the production at a low temperature, together with the possibility of adding up to 50 % RA will always score better than the alternative HMA.

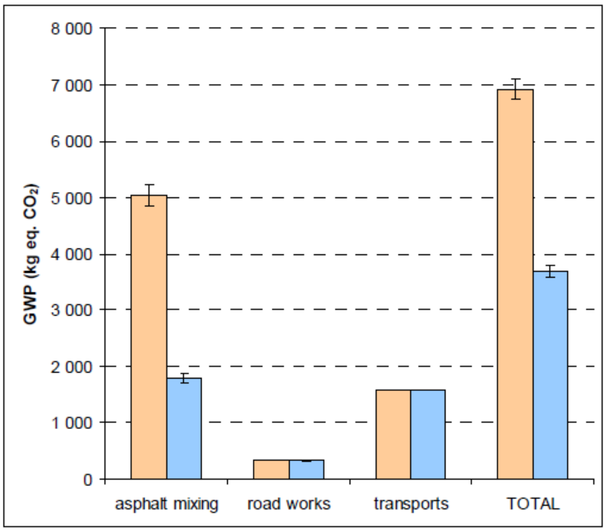


Figure 2-2: Global warming potential (blue: HWMA, orange: HMA)

(from Ventura & al 2009)

Alerts

Based on the literature analysis, one can highlight that the emissions from the asphalt plant (and consequently GWP) depend on many factors that are sometimes difficult to control. For instance, one can mention the plant design (burner capacity) and technology, the energy source, the weather conditions, the quantity produced, the aggregates humidity, the addition (or not) of RA, the period during the day, etc. The important impact of plant calibration and of the combustion process on the emission of GHG is highlighted by (Ventura et al. 2009) where CO and CH_4 emissions did not decrease during WMA production, because these emissions are highly dependent on the burner adjustment.

The comparison between results from different projects should be made carefully, taking into account the measurements and calculation methods, as well as the various hypotheses and assumptions. For instance, one can calculate the GWP indicator using a specific method, while some others consider only a few specific greenhouse gases (usually CO_2 and CH_4) or some other specific pollutants. Besides, the measurement method, the measurement specific location and the measurement duration also have an important influence on the final results.

Use of resources for energy

(Kristjansdottir 2006) reported two experiences with WAM-Foam® in Norway where a 40 % and respectively 31.5 % reduction in energy consumption have been measured in plant. Another experience with Aspha-Min® Zeolite, conducted by Eurovia GmbH, indicated a 30 % reduction in energy consumption for the asphalt plant production process (Barthel & al. 2005).

Energy consumption measurements have been performed during the production of WMA Double Barrel® Green process by (Forfylow & Middleton 2008). The comparison with a reference HMA indicated a 24% reduction in energy consumption, corresponding to $0.76 per tonne according to the local conditions and plant type used.

Measurements performed by (Lecomte & al. 2008) during WAM-Foam® production indicated a 35 % reduction in energy demand (gas).

According to (Hassan 2009) who performed a LCI from asphalt binder and aggregate production, up to asphalt mixture placement, WAM-Foam® technique permits to reduce fossil fuel consumption by 18 %.

A reduction of 55 % of the energy consumption in the plant (operated by natural gas) is reported by (Ventura et al. 2009) who performed a comparison between the LEA® process and a reference HMA. The important reduction in energy consumption is in particular due to the HWMA process LEA® that is produced at a temperature below 100 °C, while most of the other foaming processes consist in producing asphalt mixtures at a temperature above 100 °C.

Alert

Although the technology is based on the addition of water, an excessive moisture content of the aggregates has to be avoided since the removal of the excess of water will demand extra energy for drying. To minimize the use of energy, the moisture content of the aggregates has to be precisely controlled (just sufficient for an optimal foaming, but no excess!).

Use of resources for materials

In the work carried out by (Ventura et al. 2009) the authors consider the use of material resources from the asphalt plant up to the construction of the pavement. Processes such as crude oil extraction, additives production, etc have been excluded, this because there is little (or no) impact of foaming on the use of material in case of a foaming technology using water. In case of zeolite based WMA, the use of material resources will be different because of the use of this additive.

(Forfylow & Middleton 2008) evaluated WMA produced using RA and MSM™ (Manufactured Shingle Modifier) in comparison to a reference WMA without RA or MSM™.The results indicated that the use of recycling material can lead to comparable or even better mechanical performances of the asphalt mixture (more details in the “performance” paragraph)

There was no other information found on the impact of foaming techniques on the use of resources for materials, in the literature sources considered for this EDGAR deliverable. This is probably due to the fact that the use of resources for materials for foamed asphalt is not very different from a reference hot mix asphalt.

Alerts

When only the new binder is foamed (and not the old binder present in the RA) the effect of foaming on the workability and compactability of the mixture will be relatively less. This may impose a threshold on the use of RA.

Based on the reduced binder ageing, WMA and especially foaming techniques would potentially allow a higher RA dosage in comparison to conventional HMA. However, for both

HMA and WMA, in case of an important RA content (> 30% in mass) the effects on the mix design and further mechanical performances cannot be neglected. In this case, a specific analysis has to be conducted in order to identify the needed modifications in comparison to HMA without reclaimed asphalt.

Air pollution

The environmental benefits of WAM-Foam® are discussed in (Kristjansdottir 2006) where a study indicated that the fume emissions during warm mixture production were negligible compared to the emissions during hot mixture production (WAM-Foam® production in the range of 2-10 % of the fume emissions of HMA production). Another experience with WAM-Foam® in Norway showed a 31 % reduction in CO_2 emissions and 62 % reduction in NO_x emissions for the WAM-Foam® process (with 15 % RA). The same author reported an experience with Aspha-Min® zeolite where the measurements indicated a 75 % reduction in fume emissions (26 °C reduction in production temperature).

(Forfylow & Middleton 2008) performed some emission measurements during the placing of a WMA produced using the Double Barrel® Green process. Emission tests, conducted on the stack of the baghouse during WMA production, indicated an overall 10 % reduction in CO_2, CO and NO_x while a slight increase in sulphur dioxide (SO_2) emissions has been measured (note: WMA contained RA and shingles).

An extensive emission measurement campaign has been performed by (Lecomte & al. 2008) for WMA produced using a foaming technique. Several air pollutants emitted by the chimney and at three locations in the mixing plant have been measured. The results showed a drastic reduction in GHG and a considerable decrease of fume emissions and workers exposure. One can mention that CO has been reduced by 8 % and NO_x by 60 %, while SO_2 and dust have been reduced by approximately 25-30 %. Exposure measurements on the paving site were found to be well below the limit values for both HMA and WMA.

Measurements of NMGOC (Non-Methane Gaseous Organic Compounds) emissions performed in plant by (Ventura et al.2009) indicated a reduction of the emissions due to the production of WMA. These results were also consistent with laboratory experiments by the authors. The authors finally mentioned that the reduction of TOC (total organic compounds) emissions can be directly correlated to the temperature decrease (laboratory measurement).

Applying the BEES methodology, (Hassan 2009) performed the calculation of 10 different environmental impact factors. The calculations showed that WMA provides a reduction of 24 % on the air pollution impact compared to HMA. For the other environmental impacts (global warming, acidification, eutrophication, fossil fuel depletion, water intake, smog, ecological toxicity, human health non cancer and cancer), an average reduction of 15 % was calculated.

Alert

In (Ventura et al. 2009), the authors mentioned some limitations of the environmental study carried out. One can highlight that additives information was not included (for production process and transport). This might be because of a lack of information on the environmental impact of the production and use of additives.

Compared to measurements in the asphalt plant, the measurement of air pollution on the road site is even more complex and the various assumptions and measurement conditions have to be taken into account during the evaluation. Due to the low exposure levels of the workers, some measurement methods do not have a sufficient accuracy to detect differences between variants and products.

Health and safety

Although difficult to quantify, the temperature reduction is expected to have a positive impact on health and safety (less fumes, less burning injuries, …).
When using additives, the REACH legislation applies (see paragraph 1.4).

Alert

Health and safety are difficult (and expensive) to assess and require very specific competences. Thus, very little information was found on this topic.

Financial cost

Some cost related information can be found in (Hassan 2009) who indicated that the increase in cost due to WMA production relates to royalties and plant modification costs (note: this study did not consider the use of zeolites). A calculation example was provided for the WAM-Foam® technique where WMA costs were estimated to $90.41/tonne (compared to $90/tonne for conventional HMA), when distributed over a 20-year production plan.

When zeolites are used for foaming, the cost of the zeolite will be a dominant factor in the financial cost.

Additional information concerning financial costs can be found in paragraph 2.5.

Recyclability

There is no impact expected of the foaming technique on the recyclability of asphalt; this because foaming techniques in principle only require some water for the asphalt production.

No information has been found related to the recyclability of zeolite based WMA. However, the project team does not expect any problem with recyclability, considering the small amount and the chemically inert nature of zeolites in asphalt.

Alert

In case there are additives (other than zeolites) used, for instance additives to improve binder/aggregate adhesion and reduce the moisture sensitivity of the asphalt, the impact of the additive on recyclability has to be considered. We refer to chapter 7 (Additives) for more information on this topic.

Performance

In 2006-2010, the Belgian Road Research Centre BRRC and Nynas Belgium collaborated in a project subsidized by the Flanders region (IWT 050406-project), aiming at the evaluation of the performance of WMA and HWMA, compared to HMA. The objective was to achieve similar performance, as it was acknowledged that there would be no environmental benefit on the long term if the performance were poor. In the laboratory study, it was shown that the use of zeolites had no adverse effect on the mix performance when the temperature decrease was limited to 30 °C (De Visscher et al. 2010). Larger temperature decreases reduced the compactability and increased the moisture sensitivity of the asphalt. The technique with zeolites was also successfully applied in a road trial in 2010 (Assenede, Flanders, Belgium), where it was placed next to a reference HMA. Up to this date, there is no difference observed in performance between both sections. Direct injection of the water into the bitumen using a foaming unit was also studied in the same project (Soenen et al. 2009). This technique turned out to be more complex in the laboratory, because of the sensitivity to many parameters (remaining moisture in the aggregates, exact water content, time between foaming, mixing and compaction, need for an active filler to achieve satisfactory performance,…). There was also an evolution observed of the performance after compaction (“curing effect”). In general, moisture sensitivity of the final mixture was the critical performance characteristic. BRRC recently performed moisture sensitivity tests on cores extracted from WMA pavements (foaming by direct water injection through a foaming unit). These tests revealed a critical reduction of the moisture sensitivity, compared to HMA.

(Kristjansdottir 2006) indicated that field compaction was improved through the use of WMA instead of HMA; this being linked to an improved mixture viscosity. The author also analysed several laboratory and in situ performance tests of WMA. Following elements were highlighted:

- Laboratory and field trials conducted and reported for the WAM-Foam® production proved to be rather similar to the results obtained for HMA.
- Similar results have been obtained for WMA with zeolite than for the reference HMA. The use of an anti-stripping agent to counteract moisture damage and rutting potential with decreasing temperature was suggested (for zeolite).

In (Forfylow & Middleton 2008) the authors evaluated the mechanical performance of Double Barrel® Green WMA incorporating various percentages of RA and MSM™ (Manufactured Shingle Modifier). It was found in particular:

- The Double Barrel® Green process did not harden the binder to the extent of what would be expected with the RTFO test.
- Rutting susceptibility (evaluated using Asphalt Pavement Analyzer APA): RA and MSM™ have a minimal impact on the rutting susceptibility and the various mixtures have not been found susceptible to rutting.
- The addition of 15% RA does not affect significantly the resilient modulus for WMA produced with the Double Barrel® Green process. On the other hand, complex modulus testing highlighted the influence of MSM™ and RA that increase the complex modulus.
- The WMA mixtures incorporating RA and MSM™ are not susceptible to moisture induced damage. However, the virgin WMA mixture did not meet the requirements.

(Van de Ven et al. 2012) proposed an evaluation of the performance of the half warm process LEAB® by examining four functional properties:

- Water sensitivity (ITSR)
- Stiffness modulus (four-point bending test)
- Resistance to fatigue (four-point bending test)
- Resistance to rutting (triaxial test)

The results indicated that the LEAB® technology can produce HWMA with performance and durability equivalent to HMA. The authors also investigated the compactability of the HWMA and concluded that workability and compaction is not a problem; standard pavers and rollers can be used. It is however highlighted that vibrating compaction shall not be used with LEAB®.

Alerts

Some of the authors mention a higher water sensitivity of WMA produced using a foaming technique. This might indicate that some additives may be necessary or that the mix design and production temperature need to be modified in function of the required performance.

The production in laboratory of WMA with bitumen foaming (particularly with the techniques of direct water injection or management of the aggregates moisture) is a complex procedure and its representativity for large scale plant production is uncertain. Consequently, the representativity and validity of performance testing on laboratory produced mixtures could also be questioned.

The production process of foamed HWMA or WMA in the plant is in many aspects more critical than the production of WMA. The exact control of the moisture (initial moisture content and moisture content after heating) is crucial for the environmental performance and even more for the functional performance.

2.2.3 Conclusions

The analysis of the literature related to foaming techniques highlighted in particular the important variations in air emissions and energy consumption in plant, depending on the project considered. These variations are due to many local factors such as plant design (burner capacity and adjustment) and technology, recipe produced, period of the day, weather conditions and aggregates humidity. One can also observe an important difference if the techniques are produced below or above the water boiling point (100 °C). Based on this, the comparison between two different experiences without taking into account the different parameters and the measurement methods and sequences is dangerous. As a general assumption, one can however claim that at least 20 % energy and GWP decrease can be obtained in the production stage by applying theses WMA techniques (assuming a proper water management). HWMA obviously permits to increase the savings up to 50 %, this by working at a temperature below water boiling point (provided that the moisture content of the aggregates is carefully controlled).

Moisture content (of the aggregates and/or the asphalt mixture) and water management during the production process and laying phase are two important parameters in order to guarantee energy (and emission) savings and satisfactory mechanical performances of the final mixture. An excessive moisture content of the aggregates has to be avoided since the removal of the excess of water will demand extra energy for drying. A poor water management can also lead to a more important water susceptibility of the final mixture produced.

WMA produced using foaming techniques sometimes requires the use of additives. The impacts of the additives on sustainability shall also be considered (see chapter 7 “Additives” for more information).

Based on the reduced binder ageing, WMA and especially foaming techniques would potentially allow a higher RA content in comparison to conventional HMA. On the other hand, when only the new binder is foamed, this also imposes a threshold on the proportion of RA. Nevertheless, a high proportion of RA in WMA requires a correct mix design, preliminary testing of the mix performance, and analysis of the production procedure.

Due to the management of the humidity and to the injection process in plant (nozzle, pressure, …) the plant production of foamed WMA and HWMA can be more complicated than for some other WMA techniques. However, WMA produced using foaming techniques (water injection) is widely applied. A reason is that no additional costs (additives) are expected, except the initial plant modification or adjustment that is required at the beginning. A large variety of producers propose foaming units for asphalt plants. Note that the various production processes are not always equivalent when considering the characteristics and performance of the final mixture.

The production of WMA using the foaming technique in a small scale laboratory facility does not necessarily correspond to the production in plant. Therefore, performance testing on laboratory prepared specimens could sometimes be questioned.

We can finally conclude that WMA produced using foaming techniques can potentially lead to similar performance than HMA, but performance testing needs to be done correctly on a mixture which is representative of the mixture placed on the road.

2.3 Techniques using organic additives

2.3.1 Description

The organic additives used for the production of WMA are mainly synthetic waxes. Waxes with a melting point in the range between service temperatures and production temperatures of asphalt have the potential to reduce the viscosity during production (in the molten state), while increasing the stiffness at service temperatures (in the solid state). Waxes are usually added in WMA at a rate of 2-4 % by mass of the binder.

Waxes are usually added during the production stage at the asphalt plant or mixed with the binder prior to plant delivery. The added wax will then melt during the production process and thus improve the asphalt mixture workability and compactibility during the laying phase. Based on this principle, waxes allow to decrease the production temperature of asphalt.

The first applications of organic additives for the production of WMA date from 1997 with the use of Fischer-Tropsch wax (Sasobit®) in Hamburg.

The use of organic additives for WMA production presents various potential advantages among other:

- No plant modifications, production easiness.
- No (or reduced) risk for plant workers in comparison with some chemical additives.
- A good recycling potential at the EOL stage.

A non-exhaustive list of products used for WMA production with organic additives is maintained by the project team.

2.3.2 Impact on sustainability criteria

Global warming potential

The various sources analysed did not provide any relevant information related to GWP of techniques using organic additives. As for the foaming techniques, there will be a positive effect from the reduction of the production temperature, but the impact of the organic additive production and use on GWP shall also be considered.

Use of resources for energy

In (Aurilio 2009), the author presented a 1 km test section in Ottawa (Canada) where Sasobit® wax has been used (at a rate of 1.5 % of the total binder content) in a mixture containing RA. The energy savings for the plant production were estimated at around 30 % for this test case.

In (Butt et al. 2014), the authors performed a life cycle assessment focusing on the energy used for binder and additives at the project level. A framework for the calculation of feedstock energy allocation for bitumen and additives (wax, polymers) is proposed by the authors. The paragraph dealing with wax additives is especially interesting for the purpose of the EDGAR project. The suggested framework is then applied through an application example based in particular on the data from (Stripple 2001). However, this calculation example considers only conventional HMA.

Use of resources for materials

The various sources analysed did not provide any relevant information related to the impact on the use of resources for materials. Except for the use of the additive, no significant impact is expected on the use of other materials.

However, one could consider the use of waxes to improve workability and compactability of mixes with high RA content. This would lead to an increased use of RA, and a decrease of the use of new binder and aggregates from primary sources.

Air pollution

Some references dealing with the air pollution aspects of techniques using organic additives are discussed in paragraph 2.5, where a comparison is made between various WMA techniques.

Health and safety

Some references dealing with the health and safety aspects of techniques using organic additives are discussed in paragraph 2.5, where a comparison is made between various WMA techniques.

Financial cost

(Aurilio 2009) reported that the additional cost of Sasobit® is estimated in the order of $4-5/ton in comparison to a reference HMA.

Some references dealing with the financial aspects of techniques using organic additives are discussed in paragraph 2.5, where a comparison is made with some other techniques.

Recyclability

The various documents analysed did not provide any relevant information related to the recyclability of bituminous mixtures containing organic additives. However, the project team could not think of a possible problem that might obstruct recyclability.

Performance

In the Flemish project conducted by BRRC and Nynas Belgium between 2006-2010 (see previous paragraph on foaming techniques), the use of Fischer-Tropsch wax was considered. It was shown that similar performance can be achieved, but not with any type of wax and binder. The melting and crystallisation of the wax has to occur in the right temperature range and the bitumen needs to be selected as function of the wax content, in order to obtain a binder with appropriate stiffness. Similar performance was obtained as for the reference HMA, in the laboratory performance tests and on the road trial in 2010 (Assenede, Flanders).

(Kristjansdottir 2006) proposed an analysis of various laboratory and field studies of WMA with Sasobit® wax. The author mentioned in particular that Sasobit® wax leads to good performance in terms of moisture susceptibility and rutting. Sasobit® as a compaction aid in high RA content mixtures had no adverse effect on pavement performance.

Most of the information related to organic additives concern Fischer-Tropsch waxes (Sasobit®). This type of wax may lead to a rutting resistance that is even better than conventional HMA, making it very useful for heavy loaded surfaces such as airport pavements, bus lanes or container areas. However, it has been found that WMA containing waxes are more brittle in the low temperature range. This has been for instance highlighted by (Bueche 2011) who used a similar base bitumen for both WMA and HMA.

One can finally mention (Edwards 2008), (Wagner 2010) and (De Visscher et al. 2008) where a comparison between different types of waxes is proposed.
Some other references dealing with the performance of techniques using organic additives are discussed in paragraph 2.5.

Alert

Different types of waxes can be found. These waxes have various types of physical composition and also different melting points. Thus, the mechanical behaviour of mixtures with waxes depends on the type of wax used, particularly its melting and crystallization behaviour, as illustrated by (Soenen et al. 2008).

Low temperature performance of WMA with waxes is often reported to be inferior to that of HMA and this is explained by the increased brittleness in the low temperature range. A solution could be to use a softer base binder to compensate this effect. On the other hand, this would lead to a higher susceptibility to rutting, but this is not necessarily a problem. Knowing that the wax stiffens the binder, it is possible to obtain at least equal stiffness with a softer binder with wax than with a harder binder without wax .

2.3.3 Conclusions

Foaming techniques using organic additives are related to the use of waxes. Various types of waxes can be found, with differences in chemical composition that have an impact on the mechanical performance of the mixture (Soenen et al. 2008).

Considering the more widely applied waxes (Fischer-Tropsch wax), one can conclude that the mechanical performance can be at least as good as the performance of a control HMA. It is worthwhile to mention that the addition of wax can have a very positive impact on the rutting resistance of the asphalt mixture if the wax is solid in the rutting susceptibility domain (approx. 60 °C). On the other hand, the addition of wax can lead to a more brittle and sensitive material in the low temperature domain (Bueche 2011). Using a softer base binder could counteract this phenomenon.

The literature analysis and author's experience also revealed very limited information related to organic (and chemical) additives and their environmental impact. Thus, an exhaustive LCA is very complicated to perform and some important assumptions have to be made. Considering the dosage in waxes (approx. 2- 4 % by mass to the bitumen), the effect of this additive on the life cycle and on the mixture costs cannot be neglected.

2.4 Techniques using chemical additives

2.4.1 Description

Numerous chemical additives for the production of WMA can be found. These chemical additives fulfill one or more of the following roles in the mixture:

- Adhesion promoters (such as adhesivity dopes), to improve the binder/aggregate affinity.
- Surfactants, to decrease the surface tension and thereby improve the wettability of the aggregate by the binder.
- Emulsifiers, to lower the viscosity of the binder.

Products that combine these different roles have a positive effect on the workability and compactability of a bituminous mixture, allowing to reduce the production and compaction temperature.

The main advantage of using a chemical additive for temperature reduction is the ease of implementation in the production plant. Most products require little or no modifications to the plant equipment. Chemical additives also present the advantage of being very "active", meaning the dosage can be lower (sometimes by a factor 10) than the dosage used for some organic additives (can consequently reduce the price per ton of asphalt, provided the price of the additive is not excessive).

One of the major discussion points related to chemical additives concerns the life cycle impacts and related grey energy for the additive production. The recipes and processes of chemical additives are usually kept confidential by the producers, meaning that the life cycle impact assessment and grey energy consumption are difficult to assess. The calculations are often based on information and advice provided by the producers.

A non-exhaustive list of products used for warm mix asphalt production with organic additives is maintained by the project team.

2.4.2 Impact on sustainability criteria

Global warming potential

In (Carbonneau et al. 2008), the authors measured (plant chimney) a CO_2 reduction between 5 % and 30 % during WMA production (processes based on the control of binder rheology by chemical additives and the coating sequence). (Béghin et al.2012) measured a similar reduction at the plant (32 %) with another type of chemical additive which allowed a temperature reduction of 30-40 °C.

(Leng & Al-Qadi 2011) calculated four different impact indicators for the production of SMA with both hot mix and warm mix techniques (chemical additives). One of these indicators is the global warming that was found to decrease by approximately 7 % for the whole life cycle of warm SMA (approximately 16 % for the production phase) in comparison with the control mixture.

In (Gonzalez Leon & Jensen 2012), the authors carried out a LCA for Cecabase® RT product by applying Sigma Pro software and Ecoinvent database with a calculation method based on the CML 2001. In this publication, a GWP of 4.32 tonnes of CO_2 is associated with the production of 1 tonne of the additive. Consequently, while applying only 0.4 % of the additive for WMA, about 25 % of the advantage of the reduction of the production temperature in terms of GWP was lost by the production of the additive.

Alert

As mentioned above, very little information is available regarding GWP of chemical additives. Besides, most of the published information comes from the product developers.

As mentioned by (Gonzalez Leon & Jensen 2012), the comparison between a LCA for a given product and an individual measurement in plant is not recommended. Indeed, it is important to take into account the various hypothesis and parameters on which the LCA was built.

Use of resources for energy

The energy consumption was evaluated by (Carbonneau et al. 2008) during the production of WMA in plant. In the case of a gas-fired dryer, a reduction of 16.5 % (0.9 m^3/ tonne asphalt) was found in comparison with the reference HMA. For the case of a heavy fuel oil plant, savings were estimated at 0.7 l/tonne asphalt (16 %).

The study performed by (Leng & Al-Qadi 2011) proposed a comparison between two SMA, a reference HMA and a WMA using chemical additives. The energy consumption for the cradle to site lifecycle stages (construction – transportation – production – material) was found to be 6.5 % lower for the WMA than for the control HMA (15.9 % for the production process).

A comparison between HMA and WMA using chemical additives was made by (Zaumanis et al. 2012) by making an inventory of energy flow for the asphalt mixture production (typical

Latvian case). As some information related to the production of the additives production was not found, the authors assumed WMA additives to be similar to bitumen. Varying the energy use for the asphalt plant, the RA content and the compaction effort, the results indicated savings between 7 % and 18 % for the WMA technique in comparison with the reference HMA.

(Gonzalez Leon & Jensen 2012), also addressed the energy consumption for the production of WMA containing Cecabase® RT (dosage 0.4 % by mass of the bitumen) through the comparison of two *in situ* experiences. A decrease of 31 % in energy consumption was measured for the WMA product in comparison with the reference HMA (thin top layer French BBTM, with polymer modified bitumen). Another measurement performed on a SMA produced in Denmark reported a reduction of energy consumption by 23 %.

Alert

As mentioned in the introduction, one of the major discussion points related to chemical additives concerns the life cycle impacts and related grey energy for the additive production. However, to our knowledge, very little information has been published on that topic.

Use of resources for materials

(Leng & Al-Qadi 2011) indicate the possibility to add more RA in WMA, because of less binder ageing. With a 10 % increase in RA usage, the construction costs of WMA become lower than for the control HMA.

(Carbonneau et al. 2008) also mentioned that, due to the decreased binder ageing, warm mix asphalt techniques should allow a higher proportion of RA addition in the mixture. This assumption would need further investigation, in particular for the mechanical performances.

One could consider the use of chemical additives to improve the workability and compactability of mixes with high RA content (without necessarily decreasing the production temperature). This would lead to an increased use of RA, and a decrease of the use of virgin binder and aggregates.

Alert

There is very little or no information available on the use of resources for the production of the additives.

Air pollution

(Carbonneau et al. 2008) investigated the gases emitted during the production and laying of WMA applying a “control of binder rheology” technique. Referring to (Brandt & de Groot 1999), the authors stated that “*a temperature reduction of about 12 °C halves fume emissions on the laying site*”, mentioning also that this assumption is difficult to prove because of the low fume quantities.

A substantial decrease of the air pollution was also reported by (Gonzalez Leo & Jensen 2012). The authors made some measurements during WMA (Cecabase ® RT) and HMA production in plant. It can be in particular highlighted that TVOC (total volatile organic compounds) were decreased by 83 % thanks to WMA production. A second experiment reported a reduction of almost 80 % for bitumen fumes and dust.

According to (Leng & Al-Qadi 2011), SMA produced using a chemical additive (WMA) permits to reduce fossil fuel depletion (6.5 %), air pollutants (7.5 %) and smog (4.2 %). Considering the global environmental impact score, warm SMA proved to be 6.4 % better than the reference hot SMA.

(Béghin et al. 2012) performed measurements at the chimney of the plant (WMA with chemical additive and temperature decrease of 40 °C compared to the HMA). They reported a 25 % reduction of dust, 36 % of CO, 22 % of VOC and 31 % of NO_2.

Health and safety

(Carbonneau et al. 2008) indicates that inhalable dust values are far below the French or American standards; this for both WMA and HMA.

(Béghin et al. 2012) also performed measurements of the exposure to chemical substances of road workers on a french motorway (WMA with chemical additive and temperature decrease of 40 °C compared to the HMA). Most values were below detection limits, but this was also true for the HMA. Exposure to HAP were reduced by approximately 60 %.

The impact on health and safety of road workers is sometimes difficult to assess through measurements on the roadwork site, this because of the detection level of the measurement systems (Carbonneau et al. 2008). However, it is important to note that detection levels are usually much lower than the allowable limits and that even for HMA, the values are below the detection limits (Béghin et al. 2012).

Alert

Less fumes does not necessarily mean that the fumes are less affecting human health.

The results of exposure measurements for a particular technology can not be generalized to any type of technology with other types of chemical additives.

Financial cost

(Leng & Al-Qadi 2011) reported a slight increase in the construction costs of warm SMA ($71.64) in comparison to hot SMA ($69.50). The addition of 10 % RA permits to decrease the costs of warm SMA up to $67.07.

(Aurilio 2009) reported costs for a trial project that are in the order of 15-30 % more per tonne of the WMA in comparison with the reference HMA. The author mentioned that the rather important difference was mainly due to the experimental nature of the project.

Some references dealing with the financial aspects of techniques using chemical additives are discussed in paragraph 2.5, where a comparison is made with some other techniques.

Recyclability

The various sources analysed did not provide any relevant information related to the recyclability of bituminous mixtures containing chemical additives

Performance

In (Carbonneau et al. 2008), the authors provide, in addition to energy and emission measurements, some information related to the mechanical behaviour of WMA applying a “control of binder rheology” (according to the publication, we suppose that this implies chemical additives). According to the results, the mechanical performance proved to be at least equivalent to the control HMA for both laboratory and *in situ* testing.

In (González-León & al. 2009), the authors performed several laboratory tests with a WMA produced with Cecabase RT® additive. The mechanical properties of the WMA with Cecabase RT® proved to be comparable to those of the reference HMA mixture. One can particularly highlight the water resistance (Duriez, r/R=0.87 for both WMA and HMA) and the rutting resistance (4.1 % for HMA and 4.2 % for WMA after 30 0000 cycles). Some field test results lead to the same conclusions.

Some references dealing with the performance of WMA using chemical additives are discussed in paragraph 2.5, where a comparison is made with some other techniques.

WMA produced with chemical additives can have a similar (or even better) performance than the reference HMA. For instance, an extensive laboratory study performed by (Bueche 2011) obtained a similar mechanical performance for a mixture produced with Cecabase RT945® than for the reference HMA.

The use of RA in combination with WMA is partially addressed by some authors. For instance, (Carbonneau et al. 2008) observed mechanical performances at least equivalent to the control mix. This has to be verified for each particular mix and will depend strongly on the quality of the RA, but basically, warm mix asphalt techniques should allow a higher proportion of RA addition in the mixture.

2.4.3 Conclusions

Chemical additives require a substantially lower dosage than waxes (< 1% by mass of the bitumen for chemical additives) meaning that the impacts on a life cycle perspective could potentially be lower than for some organic additives. However, due to the lack of information related to the production of chemical additives, the global impacts of such additives cannot yet be assessed. Therefore, when the production of the additives is also considered, no conclusion can be drawn related to the GWP, air pollution and health and safety aspects.

2.5 WMA and HWMA techniques comparison

Some authors performed a direct comparison between two (or more) WMA or HWMA techniques. The results are presented in this paragraph.

Global warming potential

The emission reduction with the use of WMA depends on several factors. (Prowell & Hurley 2007) report CO_2 reductions between 15-30 % in the Netherlands and 45.8 % in Canada. CO_2 is generally reduced with the use of WMA and NO_x reduced in all cases. However, the exact numbers vary significantly.

In (D'Angelo et al. 2008), the authors provide an exhaustive summary of the European practice with WMA. Various WMA technologies have been considered. The reported CO_2 reduction in plant varies between 15 % (Netherlands) and 40 % (Italy). The variation between different countries can be explained by several factors such as: plant type and design, weather conditions, production rate and scale, recipes, sand and filler humidity, etc.

(Kawakami & al 2011) performed an analysis of the production stage (asphalt plant) of WMA in the Japanese context. The authors conclude that WMA reduces CO_2 emissions by about 10 % in comparison to a reference HMA.

The Dutch working group on "Asphalt at lower production temperatures" (CROW 2012) stated that CO_2 emissions can be reduced by as much as 40 % during the production. However, they also noted that production is responsible for only 31 % of the total CO_2 emissions associated with an asphalt construction (including production and transport of raw material, transport and paving of the asphalt, maintenance and milling at the EOL)

Alert

Reducing emissions through the use of WMA is dependent upon several factors detailed in (Prowell & Hurley 2007). One can mention: fuel type, plant design and operation, aggregates moisture, weather conditions, RA use, etc.

Use of resources for energy

(Kristjansdottir 2006) analysed the WMA production with Icelandic aggregates. The author estimated that a reduction of 25 % in energy consumption could be expected.

(Prowell & Hurley 2007) report burner fuel savings with WMA from 20 to 35 %. This can however be higher if the burner is properly calibrated and optimized to run at lower settings. With some WMA processes, fuel savings could possibly reach 50 % or more.

According to the European practice mentioned by (D'Angelo et al. 2008), fuel savings with WMA typically range from 20 to 35 %. However, this depends on the burner tuning. It is mentioned that savings could be higher (> 50 %) with LEAB® or LEA® techniques because aggregates are heated below the water boiling point.

According to a LCI, (Zaumanis 2010) indicated between 5 % and 18 % savings in energy consumption.

In (Papacostas 2012), the authors performed an extensive literature analysis focused on the environmental factors related to asphalt pavements. One can particularly highlight the effect of the energy source: using gas rather than diesel allows for emission savings of about 25 %. The large differences in energy efficiency between plants is also discussed: this may vary between 70 and over 150 kWh/tonne according to (Carbon Trust 2010).

In (Prowell et al. 2009), the authors reported on various WMA projects, and showed that fuel consumption ranged from 15.4 % increase to 77 % reduction (average 23 %). In an updated version of "Warm-Mix Asphalt: Best Practices", (Prowell & Hurley 2011) reported some data coming from several projects (**Figure 2-3**). In this figure, the reported case with an increase in energy consumption is related to an emulsion technology mixed at a high temperature (not WMA). Basically, for similar aggregate moisture contents and production conditions, fuel savings are related to the degree of temperature reduction.

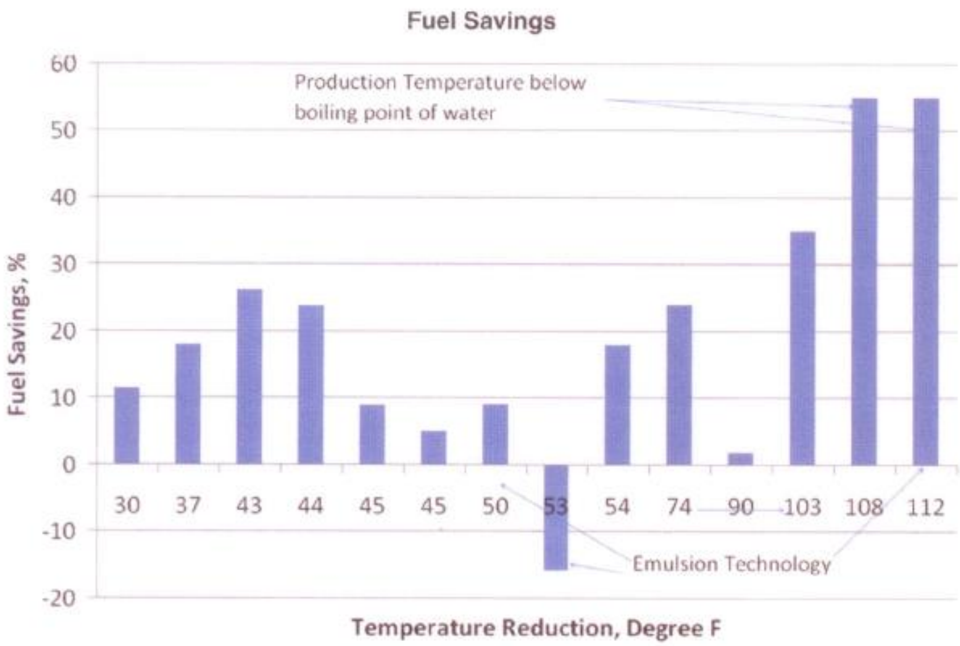


Figure 2-3: Summary of WMA fuel savings relative to HMA

(from Prowell & Hurley 2011)

(CROW 2012) also mentioned energy savings in the Netherlands by as much as 40 % during the production stage, depending on the type of WMA or HWMA technology.

Alert

Aggregates humidity is obviously an enemy of fuel savings. (Prowell & Hurley 2007) report a 10 % fuel consumption increase for every 1 % increase in aggregate moisture content.

Energy savings reported in the production stage by using WMA technologies are large. However, the energy needed for the production of the additives is rarely considered. Therefore, the true energy savings will be less, depending on the used additive.

Improving the energy efficiency of the burner can also lead to considerable energy savings.. When producing WMA, one has to be careful not to loose the energy savings by using inefficient or badly tuned burners.

Use of resources for materials

The use of resources for materials is addressed by (D'Angelo et al. 2008,) who described in an exhaustive way some of the major WMA techniques. The author also mentioned the combination of RA and WMA and its potential benefits, which are the compaction aid thanks to viscosity reduction and the decreased ageing of the binder as a result of the lower production temperature.

The combination of RA and WMA is also discussed in (Zaumanis 2010) where the author mentioned that reduced viscosity and decreased binder ageing of WMA may help to compensate the high stiffness of the binder coming from RA. He also indicates that stiff mixes such as those containing a high RA percentage could be more easily produced and compacted with WMA techniques, without decreasing the temperature as much. The aim of using the WMA techniques is thus not always to reduce the production temperature, but sometimes only to reduce the viscosity of very hard mixtures. Some experiences with mixtures with up to 90 % RA are mentioned.

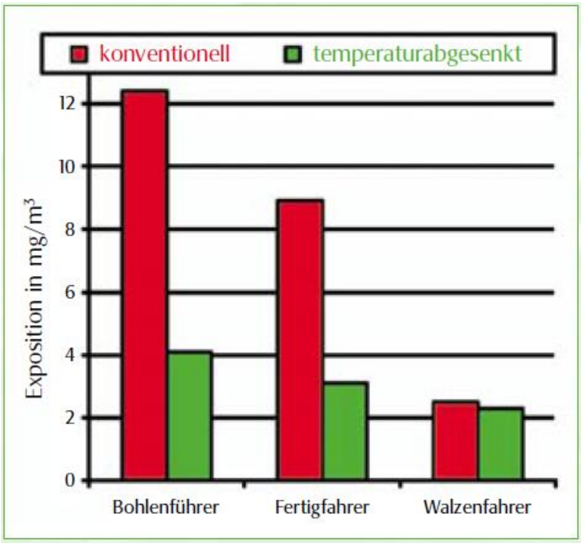
(CROW 2012) emphasizes the importance of combining RA and WMA. The environmental benefits of using RA are so important that WMA technologies should only be considered when they allow the use of high percentages of RA.

An issue of (RGRA 2012) was dedicated to the subject of increasing the rate of RA in WMA, with the aim of reducing the environmental impact to a minimum.

Air pollution

The FHWA report (D'Angelo et al. 2008) proposed a summary of the European practice with WMA. The experience in France and Italy reported VOC reduction in plant of respectively 19 % and 50 % while dust reduction in plant varied between 25 % (Italy) and 54 % (Norway).

In (Rühl 2009), some considerations are provided for air pollution of WMA in comparison with HMA. This is for instance illustrated by **Figure 2-4** which is based on several measurements (red=HMA; green=WMA). The authors also estimated a decrease in energy consumption of 5.9 % for a 10 °C temperature decrease.



x-axis: various workers (on finisher, on compactor and on road)

Figure 2-4: Exposure levels for HMA and WMA (95 %-percentil value)
(from Rühl 2009)

(Prowell & Hurley 2011) indicated that emission reduction is dependent upon several factors (temperature reduction, operational factors, plant design and operation, aggregates moisture, RA,…). The data gathered by the authors show that, with WMA production, SO_2 emissions are increased and VOCs decreased. The authors also showed that the working conditions are significantly improved with the use of WMA (reduction of fumes and aerosols).

Alert

(D’Angelo et al. 2008) mentioned that an increased emission of CO and VOC due to temperature reduction, as was observed in the United States, was not confirmed by European experience during their European scan tour. The authors explained this by the fact that smaller plants are used in Europe and correspondingly also smaller burners, making it easier to adjust the burners for lower temperatures (and reduce the unburned fuel part).

Health and safety

(D’Angelo et al. 2008) mentioned that research has shown a strong correlation between production temperature and asphalt fume production. Without reporting actual measurements results, the report mentioned that French, German and Italian data have been found to be below the acceptable exposure limits. A significant reduction in PAH (Poly Aromatic Hydrocarbons), is also indicated (30 to 50 %).

(Rühl 2008) investigated the toxicity of various commercial additives such as Sasobit® (Fischer-Tropsch paraffin), Asphaltan® A or B (Montan wax), Sübit® and Licomont® (Amidwax) and Asphamin® (zeolite). The authors also highlighted that the use of asphalt at reduced temperature offers the possibility to reduce the exposure to vapours and aerosols of bitumen, this especially for mastic asphalt.

Besides the positive impact of the reduction of fume emisions on health, (CROW 2012) emphasized the improved working conditions for the road workers, especially on hot summer days and the reduced risk of burning injuries.

Less fumes also implies better visibility during paving operations, which probably also increases safety.

Financial cost

In (Kristjánsdóttir et al. 2007), the author provided some financial considerations related to the uses of WMA in Iceland and in US context. The authors mentioned that, except in the most expensive energy market, energy savings related to WMA are usually less than the associated costs. Equipment modification or installation costs between $30 000 - $70 000 are reported for WAM-Foam® technique and between $0- $40 000 for Aspha-Min® and Sasobit®. The additional costs per tonne of mix reported are between $3.85-$4.40 for Evotherm® and $0.33 for WAM-Foam® technique ($3.96 for Aspha-Min® and $1.43-$2.86 for Sasobit®).

In (Kristjansdottir 2006), the author provides a cost comparison between traditional HMA and WMA, for the Icelandic case (**Figure 2-5**).

	HMA	WAM Foam	Aspha-min zeolite	Sasobit wax
Additional cost per ton of mix [$]	-	0.3	4.0	3.5
Cost of energy consumption per ton of mix (oil + electricity) [$]	6.5	4.9	4.9	4.9
Reduction in energy cost compared to HMA [$]	-	1.6	1.6	1.6
Calculation for total cost per ton [$]	-	89 + 0.3 - 1.6	89 + 4.0 - 1.6	89 + 3.5 - 1.6
Total cost per ton [$]	**89**	**87.7 ***	**91.4**	**90.9**
% increase or decrease	**-**	**- 1.5% ***	**+ 2.7%**	**+ 2.1%**
Installation cost and royalty [$]	-	45-55,000 (+ 5000 per year)	-	-
Example: A 30,000 ton production in a beginning year [$]	*2,670,000*	*2,677,000*	*2,742,000*	*2,727,000*
Example: A 30,000 ton production per year (after first year) [$]	*2,670,000*	*2,631,000*	*2,742,000*	*2,727,000*

* These number do not include the installation cost and royalty.

Figure 2-5: Cost comparison of HMA in Iceland and three WMA methods
(from Kristjansdottir 2006)

The economic aspects of WMA have also been discussed in (Forfylow & Middleton 2008) where a comparison between Evotherm®, Sasobit®, Aspha-min®, LEA®, WAM-Foam® and Double Barrel® Green is proposed. Equipment modification or installation costs range from $ 1000 (Evotherm®) to $ 100 000 - $120 000 (Double Barrel® Green). The only product demanding royalties is WAM-Foam®. If one considers the approximate additional cost of the mix, this ranges from 0 (Double Barrel® Green) to $3.60-$4.00 (Aspha-min®). The authors also recognized that these costs may likely fluctuate (and probably decrease) as these technologies are relatively new.

(Zaumanis 2010) proposed a comparison of costs for several WMA techniques namely WAM-Foam®, Aspha-min®, Sasobit® and Evotherm®, considering equipment modification, royalties and cost of material (additives). The calculated additional costs per ton of mix range from $0.30 (without royalties, WAM-Foam®) to $3.50-4.00 (Evotherm®).

Alert

These financial considerations should be considered with precaution, the costs being highly dependent on the region considered and the time period.

(Kristjánsdóttir et al. 2007) highlighted the necessity of up-front investment in equipment modification, materials, and training. Without these additional investments, WMA use could stagnate at the current agency-sponsored trial stage.

Recyclability

The various documents analysed did not reveal any relevant information related to the recyclability.

Performance

(Kristjansdottir 2006) provided some general considerations related to WMA performance and indicated in particular that the lower temperature used for WMA can result in incomplete drying of the aggregates. This can further lead to a higher moisture susceptibility of the mixture or require the uses of anti-stripping agents.

(Kristjánsdóttir et al. 2007) mentioned that reduced viscosity makes the best business case for widespread WMA technology adoption because it can improve compaction in case of cold weather, reduce the needed compaction equipment and reduce the risk of poor compaction when working with stiff mixtures (note: this implies using the technology without reducing the production temperature). The authors also indicated that risks associated with WMA technologies can be broadly classified into long-term performance risks and uncertainties due to a lack of experience.

(Prowell & Hurley 2007) indicated compaction aid as a benefit of WMA, this especially in the case of highly modified asphalt binders that are known to be fairly difficult to compact.

(D'Angelo et al. 2008) reported various laboratory and field performances of WMA in France, Germany and Norway. In general the performance of WMA has been found equal to or better than HMA. The authors finally i that *"on a life-cycle basis, if WMA does not perform as well as HMA, there will not be long-term environmental benefits or energy savings"*.

The performance of WMA has also been investigated by (Austerman et al. 2008) who studied two WMA additives (Advera® and Sasobit®) incorporating also RA. The major findings were:

- Workability testing (Asphalt Workability Device AWD) showed that both WMA additives improved the workability of the mixtures containing RA, this for any additive dosage (but with different improvement level depending on the dosage). However, no difference between both additives was observed through workability testing.
- Durability testing (Hamburg Wheel Tracking Device HWTD) has been used to assess moisture susceptibility. The results indicated that mixtures containing WMA additives are subject to stripping (moisture damage) at a much faster rate than the control HMA mixture.

In his Master thesis, (Zaumanis 2010) proposed some extensive laboratory testing on Sasobit® (organic additive) and Rediset WMX® (chemical additive). The evaluation of the modified bitumen properties highlighted the different mechanisms of the WMA techniques. One can also mention that stiffness (indirect tensile test) and permanent deformation (Marshall and dynamic creep test) showed that comparable performance to a HMA can be obtained with a temperature decreases down to 125 °C (reference HMA at 155 °C).

(Jenkins et al. 2014) carried out a performance evaluation of three WMA techniques, namely chemical and organic additives as well as foaming technology. Various mixtures were tested with different binders and also with the addition of RA (up to 40% depending on the layer considered). The authors concluded that:

- Stiffness tests (4 point bending) show inconsistent trends between the technologies. The control mix (HMA) can provide both higher and lower flexural stiffness than the WMA tested. WMA technology proves to have a strong influence on the stiffness.
- Depending on the WMA technology, modified binders (EVA, SBS) can provide either superior or inferior WMA mixes than the reference mix with unmodified binder.
- Fatigue tests (4 point bending) indicated in general better performance for HMA than for the WMA counterpart.

3 Cold and semi-cold asphalt technologies

3.1 Introduction

At ambient temperature bitumen appears as a semi-solid material. It is traditionally liquefied by heating at high temperatures to allow mixing with the aggregates. However, different technologies as emulsification, foaming of the bitumen with water, use of petroleum solvents or vegetal oils, allow either no heating of the aggregates or very low mixing temperature, (less than 60 °C) (**Figure 3-1**). These methods are generally referred to as cold and semi-cold technologies.

Figure 3-1 Cold recycling train using foamed bitumen
(from Wirtgen 2015)

Low temperature mixtures are used for surface or base layers of the pavement structure. When used for the surface course, they are usually only suitable for light and medium traffic. If used for base layers more traffic could be allowed.

Cold and semi-cold techniques are frequently used for in-place recycling of asphalt pavements and in-place stabilization of base layers: either emulsion based bitumen or foam expanded bitumen is used together with the milled old asphalt pavements. Relative simple mobile mixing plants established close to the construction site could also be used.

Among the different technologies, cutback asphalt, made using petroleum solvents, has been widely used in both roadway and airfields. However, because of the high volatility of some of its constituents, its use is strictly subjected to environmental regulations and considerably declining (Asphalt Institute 2007).Due to the environmental problems related to this type of asphalt it is not recommended for use. By using vegetal oils as solvent, the most severe environmental problems could be avoided.

The main advantages of these technologies are:

- the energy savings and reduced CO_2 emissions
- the simplicity of the production equipment (usually mobile)
- the possibility to perform in-place recycling (large savings in transport, storage, …)

The main disadvantages of cold and semi-cold technologies are related to the early lifestage after installation and include extended periods required to reach full strength and high sensitivity to rainfall after paving. Performance, when compared to the equivalent HMA, is also a point which requires special attention.

3.2 Emulsion based techniques

3.2.1 Description

In bitumen emulsions, the emulsifier mixed with water is the continuous phase (0.1 to 2.5 % of the total emulsion is emulsifier and 25 to 60 % water) while bitumen is the dispersed phase (40 to 75 %) (**Figure 3-2**). Bitumen emulsions are classified depending on their charge in cationic, anionic or non-ionic emulsions and further divided according to their reactivity in quick, rapid, medium and slow setting emulsions. Their choice depends on the combination between the reactivity of the emulsion and reactivity of the aggregates, and the environmental conditions (James 2006).

Depending on the type of the emulsion, the dispersed bitumen droplets can have a different size distribution that strongly influences the physical properties of the emulsion, such as its viscosity and its storage stability.

Bitumen emulsions reach their mature level of properties only after a curing period, depending on the coalescence (emulsion breakdown) speed. In temperate climates and under medium traffic, at least one complete cycle of seasons is necessary for the mix to mature. The curing time may be longer if the climate is cooler or more humid, the traffic lighter - and conversely. Presence of water, aggregate-emulsion reactivity, binder film coalescence and cohesion build-up also affect the emulsion breakdown phase (Serfass et al. 2004, Asphalt Institute 2007)

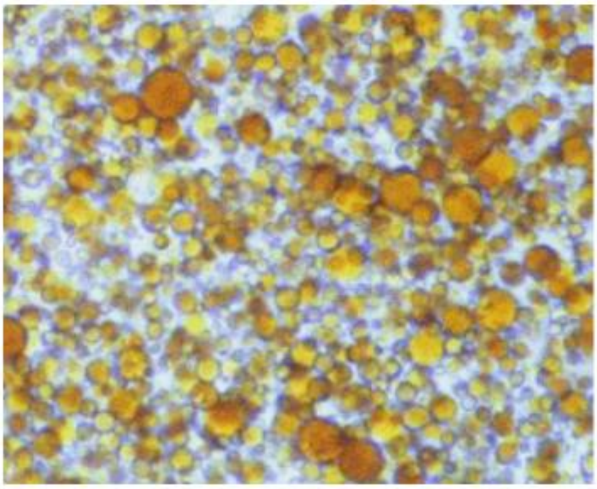


Figure 3-2 Micrograph of asphalt emulsion
(from James 2006)

3.2.2 Impact on sustainability

Global warming potential

Figure 3-3 shows the calculated CO_2-emission for rehabilitation of a 1 km section in Ontario, Canada using cold in-place recycling (CIR) based on emulsion and based on foam expanded bitumen (CIREAM) compared to the traditional method of milling and a new HMA overlay (Alkins et al. 2008). For this example, the CO_2-emission was reduced by more than 50 % compared to the traditional method.

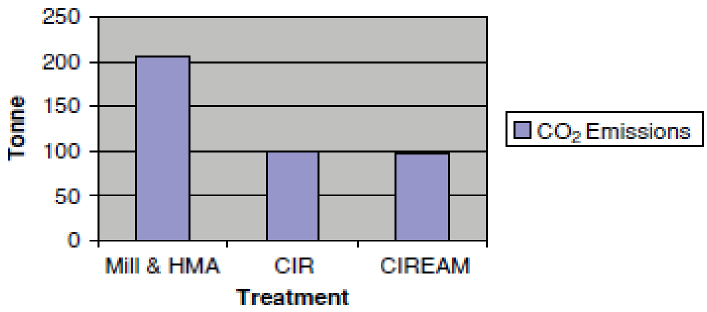


Figure 3-3 Emission of CO_2 for rehabilitation of a 1-km section in Canada
(from Alkins et al. 2008)

Use of resources for energy

As the mixing is done without heating or at low temperatures (<60 °C), the use of energy is significantly lower than for warm or hot mix asphalt. Huang (2009) estimated the energy use to about 10 % of the energy required for hot mix asphalt.

The in-place recycling process allows for substantial energy savings, not only in heating, but especially in transport. The transport savings concern the transport of new aggregates to the plant/work site and the transport of milled material to the plant and back to the worksite.

Alert:

Some energy is obviously necessary to produce the emulsifier and make the emulsification/foaming. How small these energy needs are was not found in the literature (but probably small compared to the possible energy savings with cold in-place recycling).

Use of resources for materials

For mixtures witout RA, theuse of materials is expected to be approximately the same for hot mix asphalt and cold mix asphalt.

The in-place recycling process obviously saves the use of virgin materials so if the alternative is not to reuse the old asphalt pavements one could argue for savings but this is seldom the case now.

Air pollution

As the material is not heated, there will be less air pollution during construction. In the use phase, the air pollution will be approximately the same.

Health and safety

Decreased odour and smoke from the plants and working sites gives better comfort for asphalt workers and people that live by the construction site (Button et al. 2007).

The risk of burning injuries by producing and paving hot asphalt is reduced to zero.

Financial cost

The cost of cold asphalt is generally much lower than the cost of HMA, provided that the pavement lifetime is comparable. This is possible for low volume roads without heavy traffic. (Asphalt Institute 2007, Huang 2007).

For contractors who want to apply these techniques, an initial investment is required in new equipment and to train workers and engineers. Therefore, it is necessary to assure a long term security for the volume of contracts requiring these techniques.

Recyclability

Cold mix asphalt could be recycled using the same techniques as hot mix asphalt.

Performance

The material is less resistant to heavy traffic and is usually not recommended as top layer on high volume roads. The Norwegian design guidelines (NPRA 2014) limits the use to relatively low traffic volumes (1500 vehicles per day). As a sub base layer, good performance is observed compared to milling and HMA-overlay (Alkins et al 2008).

(Moddares et al 2014) did a large-scale field testing of cold in-place recycling used as a new base layer compared to traditional milling/overlay and found that the section with cold in-place recycling performed similar to the traditional method.

An interesting review on the performance of emulsion based cold asphalt mixtures is given by (Serfass et al 2010). The breakdown speed of the emulsion is said to be a critical factor for performance. The mixture has to break down quickly to build up the required internal cohesion, but when the breaking rate is too high, this results in workability problems and poor compaction levels. Void contents of cold mix asphalt concrete are systematically higher than for a hot mix with the same granular composition. However, the void content further decreases in the years following construction, due to curing and postcompaction by traffic. The review also presents an interesting discussion of the problems associated with performance testing. The test methods for hot mix asphalt are not applicable as such, because of the presence of water, the difficulty to compact to a satisfactory level and the evolution of the behaviour in time (curing).

3.2.3 Conclusions

Knowledge gaps

The current review showed few scientific papers/reports regarding cold asphalt mixes. The method has been used for several years so obviously there must exist a lot of experience among contractors and road administrators. However, it seems that little of this experience has been published and made available for the road community. Only a few studies about performance were found together with some estimates regarding reduced emission of greenhouse gases/energy use.

Laboratory performance testing is not yet at a sufficient level of development, because the mechanisms of breakdown and curing are not fully understood. This is necessary in order to develop appropriate methods to simulate/accelerate these phenomena.

Alerts

Even if the method has been used for some time, it seems from the review that performance and environmental impact have not been thoroughly documented by scientific studies.

3.3 Foam based techniques

3.3.1 Description

Foamed asphalt mixes were developed during the 1950s injecting steam into hot bitumen under high pressure to create a foaming mass able to supply the poor properties of low quality aggregates such as gravel or sand (Csany 1957). Currently, cold or warm water is used during the process in a percentage of 1 to-4 % resulting in a much more practical and less expensive foaming process. The success of the technique is due to the volume increase, reduced viscosity and surface energy that allow a fast and satisfying coating of the aggregates and to its brief curing period, that occurs as the water evaporates (Mohammad et al. 2003).

Expansion ratio and half-life are the main characteristics of foamed bitumen: the first corresponds to the maximum volume reached after the injection compared to the original volume of the bitumen, the second refers to the time needed to subside from the maximum volume to half of the maximum volume (Jenkins 2000). A minimum value of half-life is generally specified by the road authorities to ensure that in the full depth reclamation and/or cold in–place recycling processes, where foamed asphalt is most commonly used, there will be a sufficient volume of asphalt and sufficient time for mixing and coating (Blades & Kearney 2004).

Foam based techniques are different from emulsion based techniques, but when it comes to their impact on sustainability, they are very similar. The remainder of this paragraph therefore frequently refers to the previous paragraph on emulsion based techniques.

3.3.2 Impact on sustainability

Global warming potential

(Alkins et al. 2008) also considered cold mixtures with foam expanded bitumen, compared to emulsion based cold asphalt and compared to the traditional method of milling and a new HMA overlay (Alkins et al. 2008) (see **figure 3-3**). For this example, the CO_2-emission was reduced by more than 50 % compared to the traditional method.

Use of resources for energy

See §3.2.2.

Use of resources for materials

See §3.2.2.

Air pollution

See §3.2.2.

Health and safety

See §3.2.2.

Financial cost

See §3.2.2.

Recyclability

See §3.2.2.

Performance

See §3.2.2.

3.3.3 Conclusions

See §3.2.3.

4 Asphalt recycling

4.1 Introduction

In the last couple of decades, closed-loop recycling of reclaimed asphalt has become more widespread, with an increasing number of countries using reclaimed asphalt to replace a proportion of virgin aggregates and fresh binder in asphalt mixtures (EAPA 2005). Recycling asphalt has become more prevalent due to the economic and environmental benefits that it can yield relative to conventional asphalt mixtures, and the ever-growing evidence base that indicates that the technical performance of asphalt mixtures incorporating reclaimed asphalt is broadly equivalent to that of conventional asphalt, should both produced using the same quality controlled processes. Asphalt recycling can be performed either at the asphalt production plant or *in situ* at the road construction site.

4.2 Plant recycling

4.2.1 Description

Crushing and sorting of material

Plant recycling involves removing asphalt material from the site to a stockpile, which is either co-located with a plant or centrally-located elsewhere. The first stage of the process is usually to break up the material through crushing and then screen the material into the correct sizes (EAPA 2005). Crushing can be carried out using conventional crushing equipment or by using a granulator (Kuttah et al. 2012). In some cases, planed material from the road site is considered to be adequately fragmented and is therefore screened directly without further crushing.

Storage of material

The storage of material for plant recycling is an issue that requires attention. In some instances, asphalt pavement ends as unbound granular layers in heterogeneous stockpiles. This material can only be used at the low level of recycling (Mouillet et al. 2012). The use of homogenous stockpiles where the asphalt material comes from a unique and known source is much more advantageous, from a performance-based and ecological standpoint. Furthermore, sampling and characterisation of the asphalt material based on the relevant standards (EN 13108-8 and EN 932-1) can allow the material to be used at the high level of recycling and therefore, take full advantage of the benefits of reclaimed asphalt (Mouillet et al. 2012). **Figure 4-1** presents an example of homogenous stockpiles in Sweden (Kuttah et al. 2012).

Figure 4-1: Homogenous stockpiles of reclaimed asphalt material
(taken from Kuttah et al. 2012; originally published in Handbook for recycling of Asphalt , 2004)

Stockpiles of reclaimed asphalt should not be constructed too high; otherwise this increases the tendency of the material to stick together and form clusters. Outdoor, uncovered storage of material in stockpiles can increase the presence of excess moisture, which must be driven off beforehand in the plant dryer (Enell et al. 2012). Kuttah et al. (2012) recommended that stockpiles should be temporarily stored under a roof or even covered to limit the amount of excess moisture. This will reduce the amount of heating required for drying, therefore reducing energy consumption. The stockpile should also be positioned on a waterproof surface to reduce the environmental impacts such as leaching (Kuttah et al. 2012).

Methods of plant recycling

Plant recycling can be conducted using both cold and hot methods.

Cold methods of recycling involve the addition of the reclaimed asphalt at the discharge of the dryer into the hot elevator, or in the aggregates weighing scale (EAPA 2005). The new bitumen is then added to the mixture. Recycling with cold methods can normally allow between 10 and 40 % of asphalt material to be recycled in new mixes (*ibid.*). A generalised schematic of plant-based cold asphalt recycling is presented in **Figure 4-2**. To obtain the desired mixing temperature, the low temperature of the cold-fed reclaimed asphalt is often compensated by 'superheating' the virgin aggregate feed, and inducing heat transfer between the hot and cold materials in the mixer box.

Hot methods of recycling involve the reclaimed asphalt being directly preheated. This relies on having an extra dryer installed with the associated outlay of capital costs. The reclaimed asphalt is heated and dried in the second drum, and then is transferred via a separate feed to the mixer (EAPA 2005). The percentage of reclaimed asphalt via the hot method is higher than the cold with percentages between 30 and 80 %, depending on its quality. A generalised schematic of the hot method of recycling asphalt is presented in **Figure 4-3**.

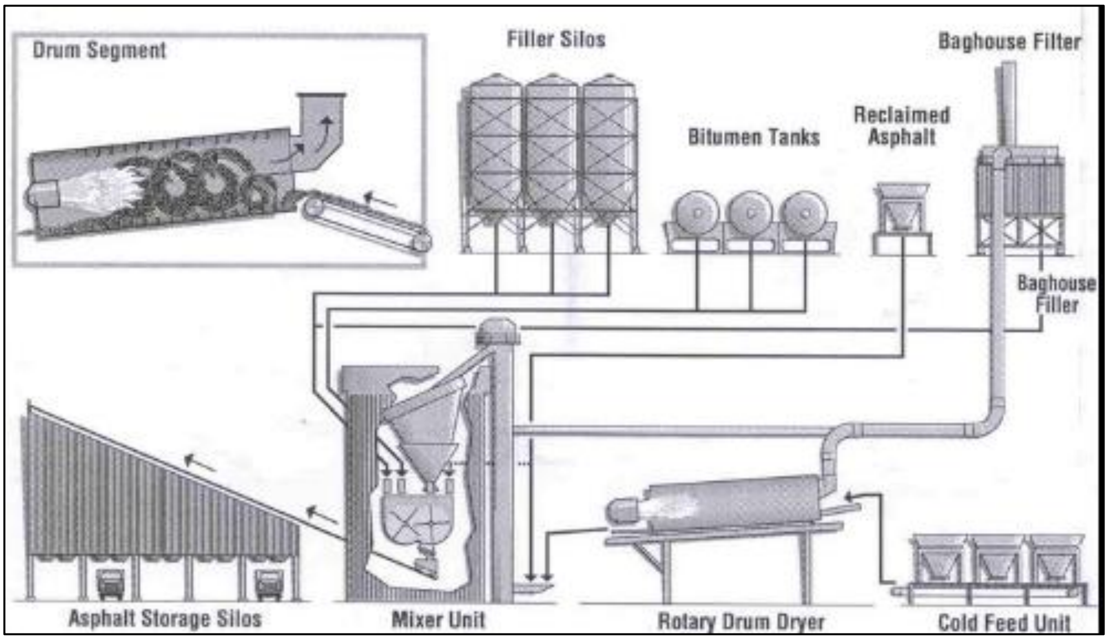


Figure 4-2: An example of the processes involved with cold recycling of asphalt material in a central plant
(from EAPA 2005)

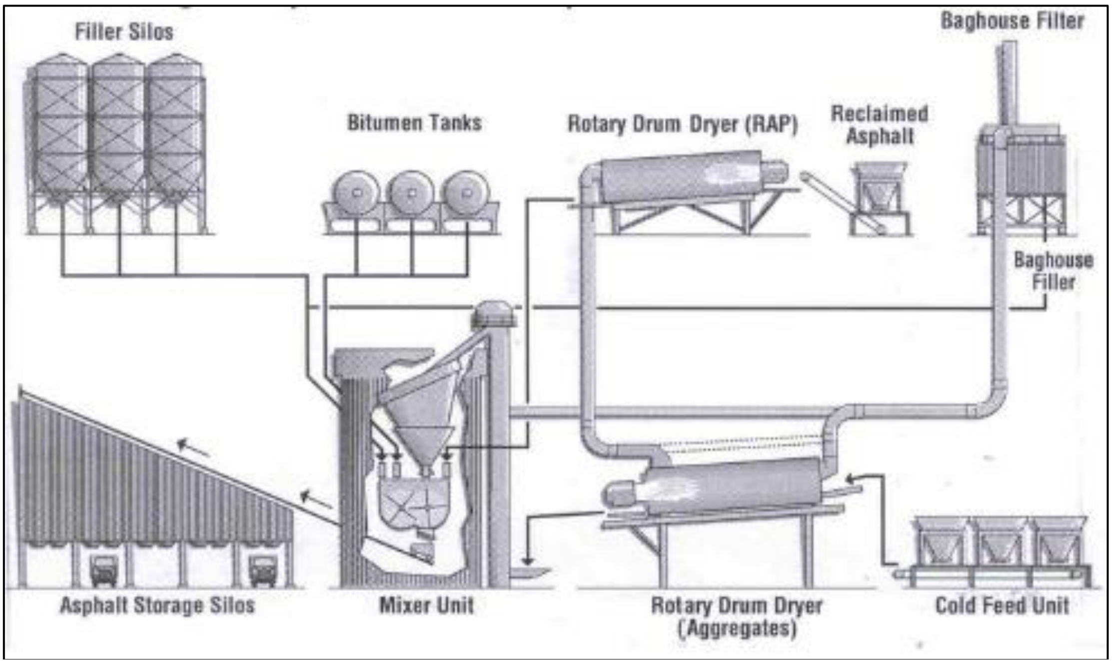


Figure 4-3: An example of the processes involved with hot recycling of asphalt material in a central plant
(from EAPA 2005)

There are several other methods that are utilised for hot plant recycling:

- Batch mixing plant (with a recycling ring) – Virgin aggregates and the reclaimed asphalt are introduced into the same drum, but in two different places. This method allows up to 35 % of pavement to be recycled.

- Drum mixer plants – Both heating and mixing take place inside the drum, there are three different variations on this method:
  - Parallel flow drum mixers – uses both direct flame heating and superheated aggregate principles. Reclaimed asphalt is added at the mid-point of the parallel flow drum;
  - Counterflow drum mixers – with the flow of hot burner gases and aggregates in opposite directions. This allows a reduction of the exit gas temperature, which contributes to an improved environmental performance through reduced heating of the reclaimed asphalt;
  - Double Barrel^{TM} drum mixers – which consist of an ordinary revolving counterflow drum surrounded by a fixed outer drum. Reclaimed asphalt is introduced in the outer shell outside of the hot gas stream. The dried virgin material is heated in the inner drum and enters the outer drum by falling through openings in the inner drum. Mixing takes place in the space between the two drums.

4.2.2 Impact on sustainability criteria

Global warming potential

Asphalt mixtures which contain recycled asphalt generally have a lower global warming potential than conventional asphalt materials (Enell et al. 2012; Wayman et al. 2010). This benefit is associated with the lower energy requirement of the recycled asphalt life cycle, where reclaimed asphalt processing has a lower energy demand than sourcing and processing primary resources such as aggregates and bitumen. Van Bochove et al. (2012) demonstrated the benefits of recycling with a cradle-to-gate scope. 25 % recycling translated to a 13 % saving in GHG emissions and 50 % recycling to 34 % savings. The same study investigated the combined effect of recycling and warm mixing at ~110°C. Warm mixing was determined to decrease GHG savings a further 9 % in the 25 % recycling scenario and a further 6 % in the 50 % recycling scenario. Overall, it could be concluded that pursuing recycling yielded relatively higher benefits than lower-temperature mixing.

Alerts

Transport is a critical factor in asphalt recycling. To maximise the benefit from recycling, the journey undertaken by reclaimed asphalt planings from site to plant must be minimised, or optimised through backhauling (Schiavi et al. 2007).

The ‘superheating’ method of hot plant recycling is only suitable for lower proportions of recycled asphalt content. It can become inefficient for higher proportions (>15-20 %; Schiavi et al. 2007) and make the CO_2e reduction potentials marginal or non-existent. Dedicated plant technologies for heating high proportions of recycled asphalt input seem to yield greater CO_2e reduction potentials (Wayman et al. 2010), though powering a parallel recycling drum in additional to the pre-existing drum in itself requires more energy (van de Wall 2012).

Use of resources for energy

The lower global warming potential of asphalt materials containing recycled asphalt arises by virtue of using fewer resources for energy in the recycled asphalt life cycle, when compared to the conventional alternative. Van de Wall (2012) asserts energy savings of 20 % for an increase in recycling rate of 10 % across the supply chain from mineral production through to road reconstruction in the Netherlands, though this seems optimistic or at least is indicative of a non-linear relationship between recycling rate and energy savings, since energy consumption cannot tend to zero in a 50 % recycling scenario.

Use of resources for materials

The primary aim of recycling is to preserve material resources. Asphalt recycling avoids the need to consume some primary resources including aggregates and bitumen.

Air pollution

Enell et al. (2012) discussed that the addition of uncontaminated RA in the hot mix asphalt does not seem to increase the total emissions or the quality of bitumen fumes in any way.

Health and safety

A concern with the recycling of asphalt is recovering material that is contaminated with tar. The high polycyclic aromatic hydrocarbon (PAH) and/or phenol content in old asphalt roads bound with tar can limit the potential for recycling as it cannot be utilised in methods of recycling where it is exposed to any heating (EAPA 2005), and can give rise to negative ecological impacts such as higher carbon emission rates and higher rates of chemical leaching (Enell et al. 2012).

Financial cost

Plant recycling can be more expensive than in situ recycling because of the transportation costs involved with taking the asphalt material to the central plant. However, this process is favoured when additional pavement layers are required or when the existing pavement is made up of different materials, which require sorting and selection (Wirtgen, 2012). The choice of plant recycling technology has implications for cost of operation, in terms of both capital outlay and on-going energy costs. To achieve higher proportions of reclaimed asphalt in mixtures (> 10 %), some form of capital outlay for a dedicated dryer or drum mix recycling technology is probably more justified, since this will counter the costs of additional energy inputs associated with superheating (and inefficient energy transfer between material components) in the longer-term.

Published literature is available that investigates the general advantages and disadvantages of using reclaimed asphalt, without focussing on one particular technique. Aurangzeb and Al-Qadi (2014) looked at the economic and environmental perspectives of mixtures with up to 50 % of reclaimed asphalt compared to ‘control’ mixtures. In terms of cost, greater savings were witnessed when higher percentages of reclaimed asphalt were utilised.

For analysis of the impacts to users during construction, calculations showed net savings in user costs of $56,000 to $94,000 per mile of single-lane highway laid with the addition of 30 % to 50 % of reclaimed asphalt. Comparison of the mixtures demonstrated that the increasing amount of reclaimed asphalt helped to reduce energy consumption and greenhouse gas emissions during the material production phase. This was supported by Wayman and Carswell (2010) who found that an SMA-based material containing 40 % reclaimed asphalt could provide cradle-to-site CO_2e savings of 29 % relative to the conventional alternative material that included no reclaimed asphalt.

Recyclability

Mollenhauer *et al.* (2012) investigated the applicability of multiple recycling with a polymer modified binder. The investigations considered three different types of polymer modified binder with up to three recycling episodes. Results were comparable between the mixes that had been recycled multiple times and the ones that contained 100% virgin material.

Although previous research work shows that mixtures with recycled asphalt are recyclable more than once, there are still many questions regarding the number of recycling loops and the quality. For example, is there a point were the quality has deteriorated to a level that recycling is not an option anymore? In that case, could downcycling be a sustainable solution or are there techniques to restore the quality of the RA (e.g. the use of rejuvenators to restore the quality of the highly aged binder)?

Knowledge gap

It is important to further investigate the potential and consequences of multiple recycling because today, many pavements that have reached their EOL already do contain RA.

Performance

The results from Aurangzeb and Al-Qadi (2014) were based on the assumption that the performances of different mixes are similar. If the performance quality of the reclaimed asphalt is less than that of the control mixtures, then more interventions of maintenance and rehabilitation activities will be required, which would offset some of the benefits discussed above. Therefore, Aurangzeb and Al-Qadi (2014) conducted analyses of the breakeven performance level using performance scenarios. The results showed that the use of 30 % reclaimed asphalt mixture would still produce an economic advantage with up to 81 % performance.

A selection of research projects and studies have produced positive results for the performance of reclaimed asphalt.

The European project PARAMIX succeeded in the design and production of mixtures with a performance equivalent to reference mixtures with exclusively virgin materials. Up to 50 % of RA was used in the base courses and up to 30 % in the surface courses (type SMA). The key was to correctly characterize the RA, to select the new binder as function of the characteristics and the content of the old binder and to design the mixture based on the characteristics of all constituents (new and reclaimed).

A similar experience was made in the European project NR2C, where BRRC and LAVOC collaborated in the development of high modulus mixtures for base layers (EME) with high percentages of RA. The mix design procedure that was followed allowed to design mixtures with high performance (again equivalent to mixtures with only virgin materials), as was shown in laboratory performance testing as well as in the accelerated loading facility of LAVOC-EPFL in Lausanne.

Whilst the remit of the research conducted by van Bochove *et al*. (2012) stretched beyond just plant mixed recycled mixtures to investigate recycled and warm mix combinations, the quality of the non-conventional asphalt mixtures investigated was observed to be of comparable a quality to that of conventional mixtures.

The RE-ROAD project further explored the potential of recycling, for example by focusing on surface courses containing PMB and on the possibilities to recycle asphalt more than once (multiple recycling), while maintaining the same high level of performance as mixtures with only virgin materials. Although there is still need for further research, the perspectives are positive.

Werkmeister *et al.* (2012) evaluated the performance of two asphalt mixtures with reclaimed asphalt in comparison to a virgin asphalt mixture. Wheel tracking tests demonstrated that a higher percentage of reclaimed asphalt resulted in increased resistance to permanent deformation. For example, the use of 15 % reclaimed asphalt produced a 53 % reduction in permanent deformation, meanwhile the use of 30 % reclaimed asphalt produced in a 72 % decrease (Werkmeister *et al.* 2012).

However, some concerns may be raised about the performance of reclaimed asphalt. For example, De Visscher *et al.* (2012) discussed that the stiffness of the aged binder could negatively impact on the performance. Therefore, it is essential to characterize the aged binder and to select the new binder as function of the aged binder. The use of rejuvenators could also be a solution to restore the properties of highly aged binders. Furthermore, it requires greater energy to remove the old binder because it sticks very strongly to the old aggregate. Aurangzeb and Al-Qadi (2014) also highlighted that reclaimed asphalt is more susceptible to thermal cracking relative to the virgin mixture.

Alert

When using reclaimed asphalt there is generally more concern regarding the homogeneity and variability of the RA compared to virgin materials. This can lead to higher uncertainties in performance and higher risks. Handling and storage issues have an important impact on these aspects and special attention is therefore needed, especially in case of large percentages of RA and/or bituminous top layers for high traffic.

4.2.3 Conclusions

Knowledge gaps

It is important to further investigate the potential and consequences of multiple recycling because today, many pavements that have reached their EOL already do contain RA, which may or may not be detrimental to performance.

Capital outlay associated with recycling (whether at plant or in situ) is rarely considered. The advantages and break-even points associated with such technologies should be fully considered.

Alerts

When using reclaimed asphalt there is generally more concern regarding the homogeneity and variability of the RA compared to virgin materials. Special attention is therefore needed, especially in case of large percentages of RA and/or bituminous top layers for high traffic.

Transport is a critical factor in asphalt recycling. To maximise the benefit from recycling, the journey undertaken by reclaimed asphalt planings from site to plant must be minimised, or optimised through reverse logistics.

The ‘superheating’ method of hot plant recycling is only suitable for lower proportions of recycled asphalt content. The process can become inefficient for higher proportions and make the CO_2e reduction potentials marginal or non-existent. Dedicated plant technologies for heating high proportions of recycled asphalt input seem to yield greater CO_2e reduction potentials, though powering a parallel recycling drum in additional to the pre-existing drum in itself requires more energy outlay (van de Wall 2012).

4.3 In situ hot recycling

4.3.1 Description

In situ recycling allows reclaimed asphalt to be incorporated directly back into new asphalt pavement under maintenance. For hot mix in situ recycling, part removal (via scarification) and heating of the existing pavement to a certain depth is required. In the ‘repave’ process, the extracted material is then reprofiled on the road and covered with a layer of fresh, hot rolled asphalt material. In the ‘remix’ process, the asphalt scarified from the road is heated and mixed with additions of fresh bitumen and virgin aggregate, to achieve appropriately specified material. The blended mixture is then placed and rolled.

Powdered stabilising agents such as cement or hydrated lime are normally spread on the surface of the existing road ahead of the recycling operation. As the recycler advances, the powder is lifted and mixed together with the recovered material. Bitumen stabilising agents can also be added (Wirtgen 2012).

Manufacturers of in situ recycling equipment highlight a number of potential advantages of in situ recycling (Wirtgen 2012):

- Reductions in subgrade disturbance - in situ recycling can work to depths in excess of 300 mm. Minimal disturbance takes place because recycling is typically a single-pass operation.
- Shorter construction time and reduced user delay costs - in situ recycling is capable of high production rates that significantly reduce construction times compared to other methods. Shorter construction times reduce project and user delay costs.
- Safety - higher levels of traffic safety can be achieved during in situ recycling. The full recycling operation can be accommodated within the width of one traffic lane. On roads with two lanes, recycling is usually undertaken in half-widths, with one-way traffic accommodated on the opposite half during working hours.
- Environmental benefits - using reclaimed asphalt pavement reduces the amount of new material that needs to be imported from quarries and in situ recycling also reduces the amount of reclaimed asphalt to be transported, which largely reduces transportation costs.

The majority of concerns relating to in situ hot recycling arise in relation to performance.

4.3.2 Impact on sustainability criteria

The consequences of in situ hot recycling are very similar as those of plant recycling technologies. Therefore, reference is made to paragraph 4.2.2 and only the consequences that differ on the basis of the type of hot recycling (plant or *in situ*) will be highlighted.

Global warming potential

See §4.2.2.

In case of in situ recycling, there is an additional benefit due to the fact that transport of the milled material between site and plant is avoided.

The addition of cement into the process of in situ recycling can have detrimental effects in terms of increasing the embodied carbon of the mixtures.

Use of resources for energy

See §4.2.2.

In situ recycling requires even less energy than plant recycling because of the savings in transport between site and plant.

Use of resources for materials

See §4.2.2.

Air pollution

See §4.2.2.

Health and safety

See §4.2.2.

Financial cost

See §4.2.2.

The process of in situ recycling can be less expensive because of the lower transportation costs and the shorter construction time. However, high financial investments are required for the special plant needed at the worksite.

Recyclability

See §4.2.2.

Alert

Upgrading of the reclaimed asphalt (e.g. treatment with rejuvenating agents) may be more difficult to apply in situ.

Performance

See §4.2.2.

Mollenhauer et al. (2012) analysed the performance of in situ reclaimed asphalt and witnessed a number of sites that gave performance below that of the comparative control. This was attributed to poor original structural capacity and poor original material. However, the vast majority of remixed sections through in situ recycling methods gave comparable performance despite high recycling ratios.

Alert

When using reclaimed asphalt there is generally a higher risk concerning the homogeneity and variability of the RA compared to virgin materials, especially if RA from different layers or mixtures is involved. This can lead to larger variations in performance. Special attention is therefore needed, especially in case of large percentages of RA and/or bituminous top layers for high traffic.

4.3.3 Conclusions

Knowledge gaps

Capital outlay associated with recycling (whether at plant or in situ) is rarely considered. The advantages and break-even points associated with such technologies should be fully considered.

Alerts

When using reclaimed asphalt there is generally a higher risk concerning the homogeneity and variability of the RA compared to virgin materials, especially if RA from different layers or mixtures is involved. This can lead to larger variations in performance. Special attention is therefore needed, especially in case of large percentages of RA and/or bituminous top layers for high traffic.

The perception of lower performance associated with in-situ recycled asphalt mixtures is still apparent. No definitive answer can be determined in relation to this question based on the research considered in relation to this review.

5 Secondary and open-loop recycled materials

5.1 Introduction

The use of secondary and recycled materials has become increasingly popular in the construction industry and their use in the construction of asphalt pavements is no exception. Use of secondary materials (i.e. those derived as by-products from other industrial processes), and open-loop recycled materials (materials that are recycled but not to their original use) contributes to sustainable development since it helps to reduce the amount of material that is sent to landfill and minimises the extraction of natural resources (Hassan et al. 2003). It may also yield benefits in terms of reduced greenhouse gas emissions, if the processing and transport of the secondary and recycled materials is less than for the equivalent primary materials.

The addition of secondary materials to asphalt pavements is likely to reduce overall costs and produce environmental benefits. However there are some obstacles that need to be acknowledged; for some secondary materials, they may only be available in a select number of locations or widely sourced, but in small quantities (Hassan et al. 2003). Transportation costs could therefore offset some of the savings found in using the materials.

A range of secondary materials that can be incorporated into asphalt mixtures is considered in the remainder of this chapter.

5.2 Steel slag

5.2.1 Description

Steel slag is a by-product of the manufacture of steel from pig iron. There are two types of steel slag: basic oxygen furnace (BOF) slag and electric arc furnace (EAF) slag (AggRegain 2010a). Steel slag can be used in bituminous mixtures as part of the base, binder course or surface course as a replacement for primary aggregates.

The manufacture of steel involves the removal of dicalcium silicate, calcium ferrites, metal oxides and solid solutions (AggRegain 2010a). The unwanted constituents form a slag and are drained off and allowed to cool. As part of the aggregate production process, weathering of the steel slag material is commonly undertaken to reduce its dimensional instability due to swelling (AggRegain 2010a; Hassan et al. 2003).

Besides long term maturation, the addition of sand to the hot slag before cooling has been investigated with success to overcome problems related to swelling (Verhasselt 2001).

More recently, Huang and Lin (2011) discussed a treatment procedure for BOF slag, which consisted of agglomeration, cooling and disintegration. This is demonstrated in

Figure 5-1. This new method of stabilisation was understood to be able to produce more stable BOF slag.

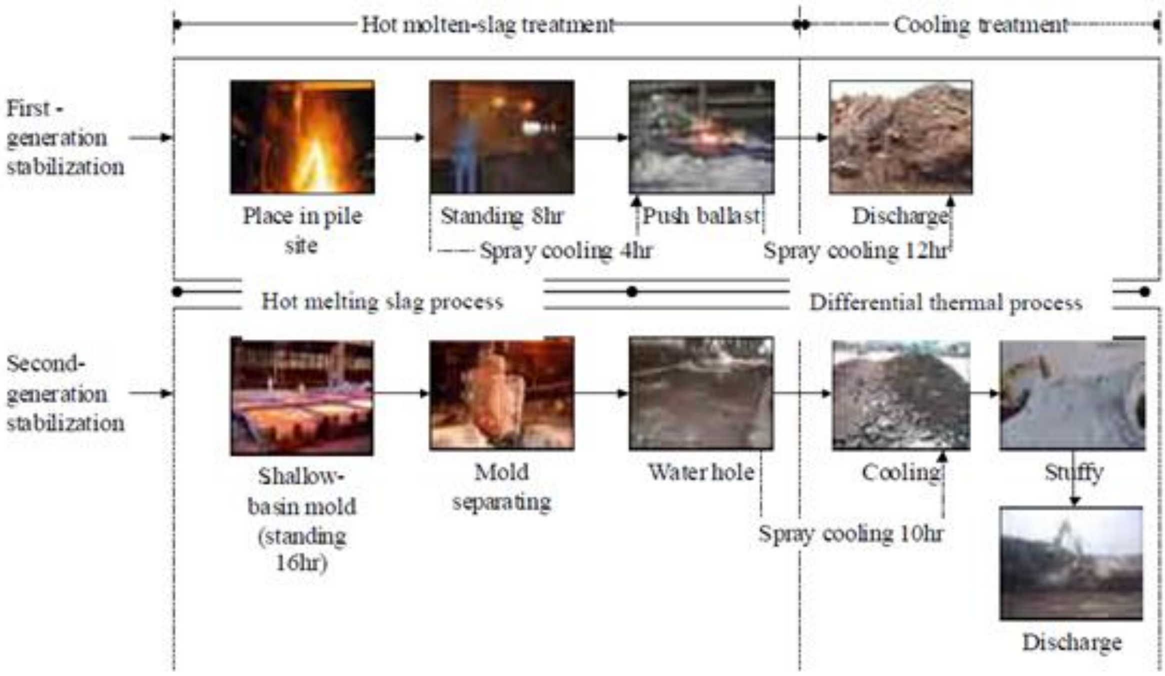


Figure 5-1 Stabilisation procedures for BOF slag

(Taken from Huang and Lin, 2011)

5.2.2 Impact on sustainability criteria

In contrast with primary materials, the life cycle impact allocation for secondary constituents such as steel slags is rather more complex. Several options may be proposed: either only allocate impacts due to the by-product treatment (e.g. crushing, sieving,…) but none to its production, or to allocate effects based on the relative economic or mass value of by-products in the primary production process. The application of one or the other of latter boundaries significantly influences the outcome of the LCA evaluation (Chen 2010). Moreover, it is worthwhile noting that steel slag may not only be re-used as aggregate in asphalt mixtures, but also as a potential replacement for cement clinker. Latter application, although not further discussed within the scope of this review, may be beneficial in terms of sustainability independently of the allocation of environmental benefits.

Global warming potential

The lower global warming potential of asphalt materials containing secondary materials arises by virtue of using fewer resources for energy in the life cycle, when compared to the conventional alternative since generally no impact is associated with the secondary materials itself.

Alert

In the case of steel slag, transportation of the heavy aggregate and the need for higher binder contents (Haritonovs et al. 2012) shall be considered, because of their negative impact on GWP. Since transport contributes substantially to the GWP, the possible advantage of using steel slags is limited to their local use only.

Use of resources for energy

Alert

The same alert as for global warming potential applies to the use of energy resources.

Use of resources for materials

The use of steel slag in bituminous mixtures avoids the need to consume aggregates from primary resources. This is particularly attractive in the surface course, as steel slag can provide high friction properties and thus provide an alternative to high polished stone value (PSV) aggregates that are more finite in terms of available resources than regular aggregates that are suitable for road construction.

Alert

The picture with regards to resource efficiency and asphalt mixtures with high proportions of steel slag replacing primary aggregates is equivocal, since the greater porosity of steel slag relative to natural aggregates requires a higher binder content (Haritonovs et al. 2012).

Air pollution

The same alert as for GWP counts also for the air pollution.

Health and safety

Leaching is one of the main environmental concerns over the use of steel slag in road pavements (Mroueh et al. 2001). However, due to the immobilisation effect by the bonding with bitumen, steel slags generally produce no serious leaching effects, although there could be some restrictions on using EAF slag. Limits with respect to leachate concentrations for (heavy) metals are set out by the environmental legislation in each country and therefore may vary throughout Europe.

Slag material should not be used if it has been left for a long time or its history is unknown (Hassan et al. 2003). This is because of the potential contamination with other materials.

Financial cost

Transport costs are normally quite high for steel slag because the material is located only at a few point sources where there are steel works, which are usually well distributed geographically (Hassan et al. 2003). Density is also a factor in relation to transportation, since vehicle loads can be limited according to weight or volume. If steel slag is denser than aggregates per unit volume then a greater mass will have to be transported to achieve the same aggregate displacement.

It is general practice that secondary materials are offered at a lower price to the costumer (asphalt producer) as compared to natural aggregates (e.g. sandstone) although precise data is not reported in literature. In such a market both parties gain an advantage since the provider of the steel slags can often avoid high costs associated with the disposal of such secondary material.

Recyclability

No literature data was identified reporting in the recyclability of steel slags present in asphalt pavements. However, it should be mentioned that some countries in Europe (such as Belgium or Luxembourg) have already a very long history of the use of steel slags in asphalt pavements both for surface as well as for base layers (Verhasselt, 1989). Therefore, at present daily practice includes the recycling of latter asphalt mixtures. No particular barriers have been reported, except for some health concerns associated with the dust emissions during the milling process.

Performance

In some European countries, the first experiences with the use of steel slags in asphalt mixtures both in the laboratory as well as in the field already date back to the late 1980's. It was reported that given the necessary attention to the volumetric stability of the steel slags, asphalt mixtures could be produced with satisfying mechanical performance (Marshall study) while characterized by high friction properties (Verhasselt 1989) and thus provide an alternative to high polished stone value (PSV) aggregates. More recently, Roe (2005) investigated the effectiveness of a road surface course, which included BOF slag. After five years, the results demonstrated that the use of BOF slag can contribute to high levels of skid resistance, which perform well in comparison with natural aggregates and can improve over time (Roe 2005). When assessing the performance of BOF slags in surface courses with the PSV test in the UK, on the basis of 10 years monitoring, some variability was observed in the results obtained though the conclusion was that in-service performance of BOF slag was broadly consistent with that of an aggregate with a PSV of 60 (Dunford & Roe, 2013). On the other hand, one of the members of the Advisory Group of the EDGAR project mentioned problems with skid resistance after polishing in the Flanders region (Belgium).

Airey et al. (2004) investigated the mechanical performance of base bituminous mixtures which featured BOF slag. They found that mixtures with BOF were much stiffer compared to regular asphalt mixes, and the moisture susceptibility, permanent deformation resistance and fatigue performance were largely comparable (Airey et al. 2004).

The recent experiences of the use of steel slags in asphalt mixtures including the major impacts on the mechanical performance of latter mixtures was reviewed by Huang (2007). Moreover, in another study by Huang and Lin (2011) some improvements in performance by using BOF slag was demonstrated. They found that the use of asphalt containing BOF slag can be compacted at lower temperatures compared to those without slag.

5.2.3 Conclusions

Knowledge gaps

It is obvious from the current review that the major part of the literature deals with the demonstration of the possible use of steel slags in asphalt mixtures, especially for surface courses given the high PSV value of latter materials. Although asphalt mixtures containing steel slags are already being recycled in practice, no research reports related with the EOL phase (e.g. recyclability) were identified.

As with many secondary materials, a question is always raised as to the quantity of impacts that should be allocated to the secondary material, given that the primary material (i.e. steel in the case of steel slag) is primary output. Allocation on the basis of economic value, mass or volume are all possible, and are all used in different situations.

Alerts

In the case of steel slag, transportation of the heavy aggregate and the need for higher binder contents (Haritonovs et al. 2012) shall be considered, because of their negative impact on GWP. Since transport contributes substantially to GWP, the possible advantage of using steel slags is limited to their local use only.

The picture with regards to resource efficiency and asphalt mixtures with high proportions of steel slag replacing primary aggregates is by no means unequivocal, since the greater porosity of steel slag relative to natural aggregates requires a higher binder content (Haritonovs *et al*. 2012).

Despite numerous reports, constant attention should be paid to the volumetric stability of steel slags before considering their use in asphalt pavements.

When evaluating the results of LCA studies involving steel slags, one should pay sufficient attention to how sustainability impacts have been allocated across the different production processes and in what way systems boundaries have been defined before drawing any conclusions. A discussion paper that considers the issues in some detail is available on the website of the World Steel Association (2014).

5.3 Fly ash

5.3.1 Description

Fly ash is a product associated with the combustion of a wide range of materials taking place on an industrial scale in the field of power generation or waste treatment. Typical sources as listed up in the Annex A of the draft revision FprEN 13043 ‘Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas’ include municipal solid waste, sewage sludge, paper sludge, biomass and coal. The latter two sources are associated with the electric power generation. Throughout Europe, the use of fly ashes arising from coal power plants has the longest history (since the 1980’s) and its application is therefore most widely spread.

Coal-burning power stations produce two types of residues: fly ash and furnace bottom ash (Reid et al. 2008). Coal fly ash, which can also be termed pulverized-fuel ash, has the most potential for use as a secondary material in asphalt pavements, where it is used as a partial replacement for the very fine aggregate ‘filler’ fraction. It is extracted by electrostatic precipitation from the flue gases of modern coal-burning power stations (AggRegain 2010d).
Coal fly ash comprises the finer fraction of the ash recovered from the gases of coal-fired power stations during the combustion of pulverized coal. Combustion conditions dictate physical properties of the fly ash (AggRegain 2010c). Coal fly ash can be (Coventry et al. 1999):

- Dry ash – taken directly from power station silos;
- Conditioned ash – with water added at source or on site to assist in handling/compaction;
- Stockpile ash – taken from stockpiles of previously conditioned ash located at the coal-burning power stations;
- Lagoon ash – recovered from storage lagoons.

Large quantities of fly ash can be recovered from storage lagoons, but this would require extra treatment costs to remove water and impurities before the material can be incorporated into the asphalt mixture (AggRegain 2010d).

Fly ash can be used as a mineral filler in hot mix paving applications by replacing natural fillers such as limestone or stone dust (US FHA, 2012b). However, field experiences associated with the use of fly ashes differ largely throughout Europe. For example, the application of fly ashes in Belgium was already introduced in the early eighties in order to stimulate the use of secondary materials and has since been a standard practice. In other countries, the practice is very limited (e.g. France) or rather new (e.g. UK).

Figure 5-2 showcases an example of asphalt containing fly ash material recently being laid in the UK (Sear & Kennedy 2010).

Figure 5-2 Laying of asphalt material including fly ash in Staffordshire, UK

(Photo taken from Sear &Kennedy, 2010)

5.3.2 Impact on sustainability criteria

As fly ash is also a by-product originating from a production process outside the field of asphalt pavements, a similar reasoning as compared to steel slags can be applied with respect to the allocation of LCA impacts. As in most cases, the impact allocation is made on economic value of the product; no LCA impact is associated with fly ash (economic value of fly ash is considered far below 1 % of the electricity produced in a coal plant). In the study described by Chen et al.(Chen 2010) the different allocation possibilities are compared but only when fly ash is used as hydraulic binder in concrete. No equivalent study for the use of fly ash in asphalt mixtures was identified.

Global warming potential

In 2013 the Danish Technological Institute (DTI) prepared an EPD for fly ash for concrete, asphalt and cement production in accordance with EN ISO 14025 and EN 15804 (DTI, 2013). In analogy with the arguments discussed above, fly ash is considered as a by-product and the allocation is made according to the financial value of the material. The EPD covers the life stages from cradle to gate. Therefore, only impacts due to transport, storage and (un)loading were taken into account. Consequently, the numbers reported for GWP (and other sustainability indicators) are quite small.

Alert

Although it may be quite logical to allocate impacts for by-products on a financial basis at present, any change of allocation would drastically alter the impact on a large number of indicators. Latter is mainly due to the very high emissions (CO_2, particles,…) occurring in electric power plants).

Use of resources for energy

A similar discussion as for the GWP can be mentioned with respect to the use of resources for energy.

Use of resources for materials

As for all secondary materials, their use reduces primary sources of materials. As generally, no impact is linked with by-products the advantage is for 100 % related to the mass percentage of replacement of primary materials.

Air pollution

The use of fly ash in asphalt mixtures can raise some environmental concerns in respect of the dioxin and polycyclic aromatic hydrocarbon content and its potential to leach into the watercourse (Hassan et al. 2003). It can also increase the risk of pollution of the atmosphere from dust due to its low bulk density. This can normally be controlled using standard procedures of good practice to reduce dust generation on construction sites (ibid.).

Health and safety

The main concern is the leaching over time of (heavy) metals present in fly ashes (Birgisdottir 2005). However, adequate leaching tests are imposed by environmental legislation in European countries in order to control such ricks.

Financial cost

No detailed information could be retrieved form literature.

Recyclability

No specific studies regarding the recyclability of fly ashes being used a filler material in asphalt mixtures were detected. However, since in some countries (e.g. the Netherlands, Belgium) the use of fly ashes has been common practice for decades already, a large part of reclaimed asphalt materials (RA) do contain fly ashes. At present, no particular distress related to fly ash in asphalt mixtures containing high percentages of RA were reported.

Performance

The valorisation of fly ash in asphalt mixtures has been reported since the early 1950s and their performance in asphalt mixtures has been well established (Huet 1968; Francken 1985, Cupo-Pagano 1997; Churchill 1999; Mogawer 1996). In general, most fly ashes are characterized by an higher stiffening power as compared to natural filler materials. Consequently, their use results in an increased stiffness of mastics and therefore of asphalt mixtures. As such they have a positive effect on the rutting resistance of bituminous mixtures.

Recently, the U.S. Bureau of Public Roads compared the strength of asphalt mixes containing various mineral fillers including fly ash. This was executed by conducting the immersion-compression test, which is used as an indicator to evaluate resistance to stripping (US FHA 2012b). Four sources of fly ash were evaluated, along with silica dust, limestone dust, mica dust and traprock dust. The results of the investigation demonstrated that mixes containing fly ash had higher retained strengths than the other filler sources tested, indicating that fly ash can be expected to provide excellent resistance to stripping (US FHA 2012b).

There have been examples where fly ash has not performed as well as expected. A survey by AASHTO (1994) indicated that eight states had used fly ash in asphalt mixtures and two had reported that it performed poorly. Although there were no discussion of the reasoning behind this evaluation, US FHA (2012b) discussed that factors such as the fineness of the fly ash and its chemical composition were most likely to affect the performance of fly ash in asphalt.

5.3.3 Conclusions

Knowledge gaps

Although fly ashes are widely used in asphalt mixture and their mechanical performance is well documented, data reported in the context of a full LCA assessment is rather scarce. Especially, little attention is paid to the EOL stage of their use.

Alerts

The environmental impact currently attributed to fly ashes (as for many other secondary products) is very small as impact allocation is based on the financial value of the material. One should however be aware that any change in the current allocation methodology would induce large effects on the LCA assessment of secondary materials.

5.4 Crumb rubber

5.4.1 Description

Crumb rubber is derived from scrap tyres, which have been removed from road and off-road vehicles, and agricultural / earth-moving equipment (AggRegain 2010b). These contain various materials such as natural and synthetic rubber, carbon black, steel, textiles, chemical and mineral additives (AggRegain 2010b). The EU Landfill Directive bans the disposal of tyres to landfill. The scrap tyres should therefore, be recycled (shredded, chipped, granulated or powdered) or used as secondary materials (tyre bales).

Crumb rubber has been used as a fine aggregate substitute in asphalt pavements. In addition, it can also be used to modify the asphalt binder by using between 18 % and 25 % of crumb rubber (Hassan et al. 2003). The processing of the rubber involves crushing and grinding the tyres using either wet or dry processes; wet produces more binder modification, meanwhile dry produces more fine aggregate. Vulcanisation reduces the effectiveness of the rubber as a modifier (Reid *et al.* 2008). **Figure 5-3** demonstrates the wet process by which crumb rubber is incorporated into asphalt pavements.

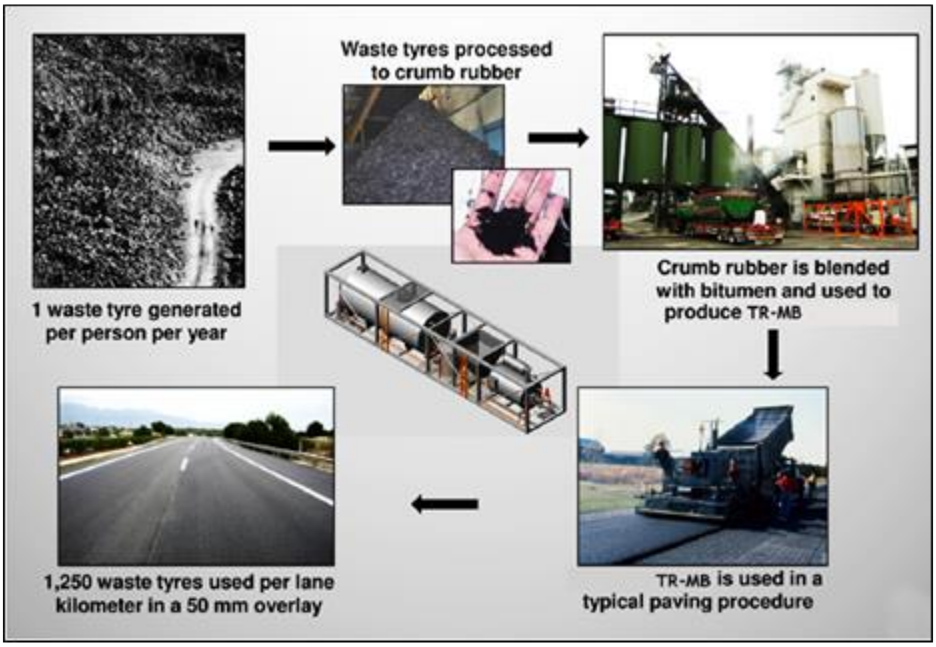


Figure 5-3 Process of producing tyre rubber modified bitumen using the wet process (Diagram taken from Presti, 2013)

5.4.2 Impact on sustainability criteria

Global warming potential

Replacement of part of the polymer fraction of the binder has the potential for large CO_2e savings, on a tonne for tonne basis, since polymers are derived from crude oil and have a high associated embodied carbon. Replacement of the aggregate fraction in asphalt is more marginal in terms of CO_2e benefit, since the energy input required to turn waste tyres into crumb, with mechanical grinding or a cryogenic process is not insignificant and could be comparable or in excess of the scale of impacts generated through conventional quarrying. Farina et al. (2014) investigated the life cycle impacts of 'wet' (binder modifier displacement) and 'dry' (aggregate displacement) scenarios. The wet process was found to be significantly positive, whereas the dry process was found to be broadly equivalent to a pavement containing conventional materials.

Use of resources for energy

Replacement of high specification polymers in polymer modified bitumen and replacement of bitumen has a positive impact since these primary materials have a relatively high embodied energy content.

Use of resources for materials

Waste derived crumb rubber that is used to replace high specification polymers in polymer modified bitumen suggests huge savings on a tonne for tonne basis, however, modifying the asphalt binder might only require 12-20 % by mass of a bituminous fraction of asphalt (Planche 2012), which might only comprise 3-8 % by mass of a bituminous mixture in total, depending on the type of asphalt. Despite this representing only 1-2 % displacement of the primary materials in the conventional asphalt mixture, it can nevertheless be significant.

Air pollution

Fume composition is an issue that is highlighted in relation to use of crumb rubber. Leaching into ground water is no worse than for conventional asphalt materials (Crockford *et al*. 1995).

Health and safety

The incorporation of crumb rubber into road pavements can be a cause for environmental concern because of the high concentration of metals and organic materials arising from the previous use of the tyre, which could leach out of the road surface (Hassan *et al*. 2003). Odours arising during the production process of rubber asphalts are also reported as a prohibiting factor, though this aspect seems to be a more anecdotal.

Financial cost

By utilising waste derived rubber and not having to dispose of the scrap tyres, significant cost savings could be realised. However, the incorporation of crumb rubber into road pavements requires extensive processing, which can increase costs.

Recyclability

Research commissioned by the Texas Department of Transport (Crockford *et al*. 1995) looked specifically at the the issue of recycling asphalt that had been previously modified with crumbed rubber. The study concluded that the material is recyclable and that asphalt mixtures containing reclaimed asphalt that had previously been modified with crumbed rubber could have 'acceptable' long term performance. Production of asphalt mixtures nevertheless requires mix design procedures to take account of the rubber in the aggregate gradation and the design of the blended binder. Emission control systems are essential for mixing plants utilising crumbed rubber.

Performance

In relation to crumb rubber, Planche's précis asserts that asphalt incorporating crumb rubber can result in increased pavement life for high volume traffic roads, and possible noise reduction when used in open-graded friction courses.

The majority of schemes involving scrap tyres have come from the USA. Reid et al. (2008) presented examples where rubber was used to replace between 2 and 5 % of the aggregate (Reid et al. 2008). Arizona Department of Transportation have successfully used ground tyre rubber in asphalt pavements, after conducting research that determined that asphalt pavements which included rubber were more durable and versatile in different temperatures, and required less maintenance. Further advantages included greater resistance to cracking and deformation under traffic loads (Hassan et al. 2003).

5.4.3 Conclusions

Alert

Appropriate precautions need to be taken in recycling to ensure that exposure to fumes are minimised through emission control. The balance of studies suggests that fumes deriving from the incorporation of crumb rubber into asphalt could pose more of an acute risk to human health that those deriving from conventional asphalt manufacture.

Appropriate procedures need to be followed when blending crumb rubber into bitumen to ensure that satisfactory performance levels are achieved from the resultant asphalt mixtures.

The reported LCA (Farina et al., 2014) was the only study that could be found on the subject and should be treated accordingly.

5.5 Shredded roofing

5.5.1 Description

The use of roofing shingle scrap has risen over the past few years, particularly in the USA. When incorporated into asphalt paving mixtures, it can modify the binder and function like aggregate or mineral filler. Typically, three to six percent (by mass) of roofing shingle scrap is added to an asphalt mixture (US FHA 2012a).

Before roofing shingles can be added into the asphalt mix, they are shredded, screened and then stockpiled. The size of the processed pieces should be no larger than 13 mm otherwise the pieces will not be fully incorporated into the asphalt mix (US FHA 2012a). **Figure 5-4** presents an example of sorted roofing shingles. Potential issues can arise during the stockpiling procedure. Roofing shingle material can resolidify if left for too long, which means it may have to be processed and screened again. This can be mitigated by either blending the material with a carrier material such as sand to prevent particles from sticking together, or by keeping the material cool by watering during the processing period (US FHA 2012a). The second of these methods is not ideal because it would require the material to be dried before introduction into the asphalt mixture.

Roofing shingles have been successfully incorporated into asphalt mixtures in the USA. The Texas Department of Transportation (DOT) used 5 % of post-industrial shingles in a section of road near Sparta, New Jersey and noted that the performance was comparable to a control section (Hassan et al. 2003). Minnesota DOT implemented a test section that contained 9 % shingles by weight of aggregate and this was also found to be performing satisfactorily (Hassan et al. 2003). Evaluations from a trial pavement section in New Jersey found that after a few years, the performance of an asphalt pavement with roofing shingles was satisfactory with no significant differences in the rut depth, cracking or skid resistance (US FHA 2012a).

Also in Europe, and in particular Belgium, research was conducted at the University Colleges of Antwerp on the re-use of reduced roofing felt or RRT in bound and unbound base layers for road construction (Van den Bergh et al. 2008). The study which included both laboratory testing as well as the construction of test sections in the field demonstrated the potential of RRT (added at about 5% in mixture) as an alternative material. Performance testing showed a high resistance to rutting, an increased modulus and a fair water resistance.

Figure 5-4 Roofing shingles sorted in the background with metal dumpsters for any rejects to be sent to landfill (Photo taken from Grefe, 2007)

Laboratory studies have demonstrated that the use of roofing shingles can improve the high temperature susceptibility and rut-resistant properties of the mix. This contributes to an improved fatigue life of the pavement (US FHA 2012a). The introduction of roofing shingles produces a denser pavement which has the effect of reducing cold tensile strengths, but does not impact on the potential for low-temperature cracking (US FHA 2012a). Due to its hardness, roofing shingles must be blended with a softer asphalt cement binder for use in the asphalt mixture. Higher mixing temperatures are normally required to sufficiently coat the shingles material (Hassan et al. 2003).

Tear-off roofing material waste can also be added to asphalt mixtures. As it often contains the presence of contaminants / debris such as nails and wood, this adds complexities to the processing of the material. Furthermore, the performance of tear off shingles has not been as positive as roofing shingle scrap. This is because it can have adverse effects on the strength of the binder and present environmental risks due to the presence of polynuclear aromatic hydrocarbons in roofing tar (US FHA 2012a).

5.5.2 Impact on sustainability criteria

As a composite of aggregate and bitumen, roofing shingle has much the same sustainability impacts as reclaimed asphalt when incorporated into new asphalt mixtures (see paragraph 4.2).

Global warming potential

See paragraph 4.2 for a summary of the benefits of plant recycling shingles to hot asphalt mixtures.

Use of resources for energy

See paragraph 4.2 for a summary of the benefits of plant recycling shingles to hot asphalt mixtures.

Use of resources for materials

See paragraph 4.2 for a summary of the benefits of plant recycling shingles to hot asphalt mixtures.

Air pollution

See paragraph 4.2 for a summary of the impacts of plant recycling shingles to hot asphalt mixtures.

Health and safety

Recycling shingles may pose some particular problems due to the nature of the oxidised bitumen that is used in roofing applications. An IARC Monograph (2013) synthesises evidence surrounding the use of bitumen and related products and several studies infer that oxidised bitumen may present a degree of carcinogenic risk due to an elevated presence of 4-6 ring PAHs, when compared to straight-run bitumen used in paving applications. The risk from the presence of these compounds would be most acute during laying and subsequent recycling of roofing products.

Financial cost

By utilising the roofing shingle scrap and not having to dispose of material, significant cost savings can be realised. The National Asphalt Pavement Association estimated cost savings between $1 and $2.80 per tonne when using an asphalt mix with 5 % of roofing shingle scrap (Davis 2009).

Recyclability

See paragraph 4.2 for a summary of the impacts of plant recycling shingles to hot asphalt mixtures.

Performance

An incremental decrease in Marshall stability is observed for asphalt mixtures which incorporate shingles up to 5 % in overall proportion, at which point it appears to level off (Aktas 2012).

5.5.3 Conclusions

Alert

Recycling expired roofing shingles into asphalt offers similar benefits to recycling reclaimed asphalt into asphalt mixtures, with much the same sustainability impacts. However, the proportion of shingles that can be incorporated into mixtures is generally lower than the proportion of reclaimed asphalt. due to a drop-off in performance which can be observed for mixtures with higher proportions.

5.6 Crushed glass

5.6.1 Description

Crushed glass can be added as a secondary material to bitumen bound materials in the base or binder course (AggRegain 2010c). The key components of crushed glass are quartz sand and sodium carbonate. Recycled glass can be separated at source, separated at recycling facilities or collected from bottle bank (AggRegain 2010c). The first and most ecologically-sound recycling solution for container glass is colour separated, closed-loop recycling back to container glass. Should the source of reclaimed glass be mixed in colour, then use as an aggregate arises as the next most viable option.

During processing, crushing can eliminate all sharp edges and the safety hazards concerned with the manual handling of the product. Glass can be crushed to either large grain sizes (larger than 5 mm) or small grain sizes (smaller than 5 mm) (Reid et al. 2008). Small grain sizes have the greater potential as a replacement for aggregate in asphalt pavements (Reid et al. 2008).

Lightweight aggregates made from expanded glass (or clays) are potential products that can be manufactured from post-consumer glass waste. To manufacture expanded glass, cullet is finely ground, mixed and formed into granules. The granules are then sintered and foamed (expanded) in a rotary kiln. This process creates lightweight spheres with a fine closed cellular pore structure. However, there appears to be little evidence of aggregates of this nature being deployed into asphalt due to the inadequate compressive strength of the expanded product.

5.6.2 Impact on sustainability criteria

Global warming potential

The ecological merit of using of crushed glass in bituminous mixtures, particularly with regards to GHG emissions, becomes highly dependent on transport distances undertaken to reprocessing, given that the glass will need to undergo some level crushing and grading to reprocess it for use as an aggregate, with both processes requiring an input of energy (Wayman et al. 2009).

Use of resources for energy

The considerations made as for global warming potential are relevant for energy consumption.

Use of resources for materials

Use of glass in asphalt reduces the demand on sources of primary aggregates.

Air pollution

No particular concerns have been elicited from the literature regarding air pollution impacts associated with the use of glass as a replacement for aggregates in asphalt mixtures.

Health and safety

No particular concerns have been elicited from the literature regarding health and safety impacts associated with the use of glass as a replacement for aggregates in asphalt mixtures, apart from the normal risks associated with manual handling of glass.

Financial cost

The prices of recylate materials, and indeed aggregates, vary from month-to-month depending on availability, levels of stock and demand. It is therefore difficult to determine the financial advantage of using glass as an aggregate substitute with any certainty. Where mixed glass cullet is produced, as opposed to colour-separated cullet that can be recycled to glass containers, aggregates appear to be a useful outlet with few competing avenues to increase demand and push up prices. Avoidance of landfill costs required to dispose of mixed cullet is an obvious advantage to utilising recycled glass as an aggregate.

Recyclability

No past research could be identified that dealt with ‘re-recycling’ of asphalt mixtures incorporating glass as an aggregate replacement.

Performance

The main concern about using glass in asphalt materials is the lack of adhesion between the bituminous binder and the smooth glass surface (Hassan et al. 2003). Elongated particles within the crushed glass can contribute to increased rates of pavement ravelling and stripping and resulting in poor skid resistance (Hassan et al. 2003).

Airey et al. (2004) determined that the use of glass cullet as a secondary aggregate only marginally reduces the stiffness modulus of an asphalt mixture. The increased moisture susceptibility of the material was also less than what would be expected for a smooth surface-textured aggregate such as glass, with and without the use of an anti-stripping agent. The permanent deformation resistance, although inferior to that of a primary aggregate mixture, was determined to be still acceptable with the fatigue performance being comparable to a control mixture of conventional hot-mix asphalt.

Glass was used in the asphalt base and binder courses of a construction project at Junction 2 on the M50. Recycled glass was crushed using a swing hammer crusher and screened to allow all material of 20 mm diameter and above to be removed (AggRegain 2003). The glass was included in an all-graded aggregate and fed through an asphalt plant cold feed system, replacing up to 30 % of the primary aggregate. An adhesion agent was incorporated into the bitumen to prevent stripping of the bitumen from the glass (AggRegain 2003). Test results showed that recycled glass in the asphalt had no detrimental effects on the performance of the pavement. There were no differences in the indirect tensile stiffness modulus between regular asphalt mixes and ones that incorporate recycled glass (AggRegain, 2003). Furthermore, the avoidance of 10,500 tonnes of material going to landfill was achieved through completion of this project, which resulted in economic and environmental benefits (AggRegain 2003).

Another case study in Switzerland used recycled glass from crushed glass bottles, incorporating 30 % into asphalt mixtures. There were issues with the adhesion between the binder and the smooth glass surface, but test results for the stability, water sensitivity and rutting of the mixture were favourable (Hassan et al. 2003). To improve the problem of adhesion, it was suggested that the surface could be roughened. This would help to make crushed glass an even more attractive proposition for use in asphalt mixtures.

5.6.3 Conclusions

Alerts

The benefits associated with using glass in asphalt mixtures are primarily resource-consumption related. Using glass in asphalt avoids primary aggregate consumption and avoids disposal of glass to landfill. The global warming benefits of such practices are marginal and dependent on the relative transport distances between facilities in the supply chain. Some special measures need to be taken to incorporate glass into surface course asphalt mixtures to ensure sufficient adhesion is achieved between glass particles and the bitumen binder.

Adhesion is asphalt materials containing glass is highlighted as a problem and adequate measures need to be employed to avoid it.

5.7 General conclusions

The primary benefit of using secondary materials in asphalt mixtures is resource conservation: primary aggregates and/or bitumen are preserved to a greater or lesser degree, depending on the specific substitute material. Incorporating secondary materials into asphalt is, on the whole, not significantly detrimental to the performance of the asphalt in the longer term and can sometimes enhance it. However, there are individual limits that need to be respected in relation to the use of each material. Some secondary materials can offer additional benefits such as reduced global warming potential, though this is often source (and asphalt mixture) specific. Each secondary material often comes with a particular drawback, whether ecologically or performance related, but these can often be accounted by considering the literature published on each one, and avoided with the correct application. The only shortfall of information in relation to the application of secondary materials seems to exist in relation to multiple recycling scenarios or ‘re-recycling’. This is reconfirmed as being an issue by Planche (2012).

Asphalt mixtures which contain secondary materials generally a have a slightly lower global warming potential than conventional asphalt materials. The size of benefit, however, can be marginal, especially if secondary materials are only used to replace a fraction of the aggregate in the new asphalt mixture. In this case, benefits are generally only yielded in terms of CO_2e reductions if the energy used to process the secondary material to the point of use in asphalt is lower than the embodied energy of the aggregates that they displace (which is relatively low compared to the majority of other construction materials). Some discussion of these issues is provided in Wayman et al. 2008 and Nicholls et al. 2010. Slightly more benefit can be realised if local sources of secondary materials (e.g. steel slag) can replace high PSV aggregates that are sourced from more widely distributed quarries. Greater benefits could potentially be yielded if the pozzolanic properties of some secondary materials (e.g. of fly ash, steel slag and glass) were utilised (Wayman et al. 2008), though this would only be possible if the opportunity to displace cement in bituminous mixtures arises (e.g. in cold asphalt mixtures).

Studies which consider the financial perspective of using secondary materials are limited. It can generally be asserted that utilising secondary materials, which might otherwise be consigned to waste, would be financially advantageous. This basic premise would come with a few conditions, however. Transport and processing costs should not be excessive. Furthermore, there should ideally not be competing uses for the secondary materials, which would increase demand and raise prices as a result.

6 Alternative and modified binders

6.1 Introduction

In this paragraph alternative binders are reviewed in terms of the selected sustainability criteria set out in Table 1.3. In accordance with the output of task 1.1 ‘Initial selection of materials, technologies and assessment criteria’, two families of alternative binders are considered namely vegetal or bio-binders and special modified binders. Synthetic binders obtained by polymerisation of building blocks derived from petroleum were not considered as green materials and are therefore not discussed any further. Although their use is already common practice, polymer modified binder or PMB are also discussed since latter binders do affect significantly the long term performance and therefore the durability of surface layers. Hence, PMB play a major role in the overall sustainability of asphalt pavements. Within the scope of this review, only applications in asphalt mixtures are discussed. Therefore, the use of vegetal binders in emulsions (e.g. surface dressings) and bio-fluxing agent fall outside the scope of this review.

6.2 Vegetal or bio-binders

6.2.1 Description

Vegetal or bio-binders are acquired by processing raw materials of vegetal origin. An example of such a process consists of the (flash) pyrolysis or thermochemical conversion of organic renewable raw materials or bio-renewable resources made available by the agricultural sector. In latter process bio-oils are obtained comprised of two major fractions: a light part used as bio-fuel and a residual heavy fraction or bio-binder. In the US, bio-oils are also termed as bio-asphalt. Examples of bio-renewable sources reported in the literature (Fini et al. 2010, You et al. 2012, Leite et al. 2012, Mohammad et al. 2012, Yang et al. 2013) include:

- Residues of wood processing industry (chips, sawing dust,…)
- Molasses of different origin (e.g. sugar industry)
- Swine manure

In other cases, adhesive resins derived from pine trees are utilized and give rise to bio-binders predominantly plant-based except for the addition of synthetic petroleum based polymers (Baillié and Delcroix 2008, Lecomte et al. 2009). Moreover, oils derived from natural sources such as from sunflower or coleseed are also applied within road applications as bio-fluxing agents, rejuvenators or as additive to synthetic binders (e.g. in the field of coloured asphalt mixtures).

The main drive to develop and investigate the use of bio-binders in the domain of asphalt pavements reported in literature is to reduce the environmental impact arising from the use of bitumen both on a material level as well as during the production of asphalt mixtures at high temperatures. Rising petroleum prices may also promote the use of alternative binders. Moreover, since vegetal binders are translucent they are also utilized as clear binders in the area of coloured asphalt pavements.

It should be noted that bio-binders are often used to replace only partially a bituminous binder. In latter case and depending on the amount blended in one can consider the bio-binder as a binder modifier (extender) or even as an additive in case of low concentrations (<10 %).

A series of about 40 literature documents (including papers, reports, short communications, leaflets,…) so far was screened while looking for available information with respect to the most important sustainability criteria. A large part of the literature sources could be directly linked to the bio-binder producer and/or supplier. The key objective of latter sources is primarily inspired by commercial or marketing goals and therefore contains very little or no substantiated data related to sustainability issues. Often only generic knowledge or ideas are illustrated fitting well within the framework of the use of more environmental friendly materials or 'green' processes. Therefore, latter information will not be discussed any further.

Only ten papers were identified to include useful information associated to sustainability criteria. All of them report results related to either the development or the subsequent use of bio-binders with an extended focus limited to laboratory performance testing of both the bio-binder as well as the corresponding asphalt mixtures. In latter way, the performance during the use phase is estimated and compared to 'classical' pavements. In several studies the applicability of bio-binders is further demonstrated by field trials. In only one extensive study ordered by the Michigan Department of Transportation, special attention was paid to a LCA assessment and environmental effect evaluation of the use of bio-binder (You et al. 2012). Other papers only mention briefly the benefits to the global warming potential, health and safety, the reduced need for primary materials or the lower air pollution mainly due to the lower reported production temperatures while using bio-binders without providing detailed data.

In the following part of the review, a more detailed overview of the literature ordered by sustainability criteria is provided. This overview comprises both alerts already mentioned by the external literature sources cited as well as based on the reviewer's knowledge or viewpoint.

6.2.2 Impact on sustainability

Global warming potential

Fini and co-authors reported on the use of a bio-binder sourced from the thermochemical conversion of swine manure as a partial replacement and modifier of a bituminous binder (Fini et al. 2010). Authors demonstrated that the addition of a bio-binder resulted in a drop in viscosity resulting in better wettability properties and enhanced mixture workability. Therefore, latter mixture can be produced, compacted at relatively lower temperatures resulting in less energy consumption and CO_2 emissions.

A similar impact of the generally lower viscosity of vegetal binders has been reported by Trigallez (Trigallez et al. 2009).

Alert

In the paper of Yang (Yang et al. 2013) a Cedar based bio-binder obtained by fast pyrolysis is proposed as a green alternative for conventional bitumen. A greenhouse gas emission of 285 kg/tonne associated with the production of bitumen is stated by the authors. However, to the reviewer's opinion it is unfortunate that no data are provided with respect to the pyrolysis process itself providing an alternative 'green' binder.

Use of resources for materials

It is reported in the literature that the production of bio-oil by the thermochemical conversion of swine manure can reduce the U.S. dependence on petroleum resources by supplementing about 9 million barrels of bio-oil per year. In 2008 about 25 million ton of bitumen was used in the production of asphalt mixtures (Fini et al. 2010). Also in the paper by Yang (Yang et al. 2013) the urgent need to develop more sustainable binders is discussed given the decreasing amount of petroleum reserves.

Alerts

Literature also draws attention to the fact that having a good idea of the exact scale of available raw material (feedstock) is quite important in order to guarantee a continuous supply to the end user (Yang et al. 2013). In some cases, in order to obtain enough quantity of biomass, one needs to designate a large land area to grow the same type of plants/vegetables. This may raise questions about responsible sourcing (contend the potential land use for other agriculture purpose than required for food production) or might destroy local biodiversity. To the reviewers opinion similar alerts as for the production of bio-fuels do apply in the field of bio-binders. In case of agricultural waste products (wood chips, swine manure,…) such questions may be possibly avoided. However, little information is reported at present about the availability of swine manure to provide a viable alternative for bituminous binders.

Use of resources for energy

In the paper of You et al., 2012 the LCA aspect of the use of bio-binders is paid attention to. However, with respect to the fast pyrolysis production process, authors refer to an old study of Williams (Williams and Whitten 1983) and to data reported by Fan (Fan and Kalnes, 2011) due to the lack of available first-hand data. Otherwise, a lot of attention is given to general environmental impact categories taking into account geographic (possible impact on local, regional or global scale) parameters (Manyele et al. 2007).

Alerts

A complete insight (in a quantitative way) of the energy consumption associated with the use of bio-binders is on the other hand missing. Also in the report by Fini mentioned above (Fini et al. 2010), authors do describe the thermochemical conversion process (at high pressure and elevated temperature) of bio-waste, but no accompanying data with respect to energy, emissions or health and safety issues were stated.

Air pollution

There was no detailed information found on the impact on air pollution although it is generally stated in various communications that lower production temperatures while using bio-binders also results in lower emissions of particulate matter or other gases such as NOx, SOx,…

Health and safety

You et al.,2012 reported that the use of bio-oils originating from the fast pyrolysis of wood brought irritation to both eyes and skin during the mixing and compaction of asphalt mixtures containing latter bio-binder although overall emissions were anticipated to be reduced.

Alert

To the reviewers opinion one has to be quite cautious to propose a pyrolysis process as a 'clean' technology. Although the starting material may originate from natural bio-mass waste, the process itself which is conducted at high temperatures and pressures generally yields harmful or even toxic waste residues such as bio-char and bio-gas by-products, which may contain cancerogenic Polycyclic Aromatic Hydrocarbons or PAHs. Nevertheless, bio-char or bio-gas by-products are in some cases assumed as such to be completely recyclable within the bio-binder production process. Consequently, they are not accounted for as a possible source of waste in an overall assessment. More data about the health and safety aspects of candidate bio-binders should be made available.

Financial cost

Fini and co-authors claim that the use of a manure-based bio-binder can reduce significantly the asphalt pavement production cost due to the large price difference between bio-binder and conventional bitumen. A production cost for this type of bio-binder around $0.5/gallon was reported where paving grade bitumen is produced at about $2 gallon (Fini et al. 2010). Moreover, it cuts the high dependency from petroleum derived energy and products.

Alert

Literature draws attention to the fact that using bio-mass sourced binders could go along with a higher cost due to the required investments and re-training of staff. However, reviewers doubt if latter cost is that important it would create a real hurdle to apply bio-binders.

Recyclability

The current literature review didn't reveal any information with respect to recyclability. This is probably due to the fact that the majority of the bio-binders are rather new and their use is currently limited. Therefore little long-term experience in the field is available at present.

Performance

Mohammed et al. reported on the laboratory performance of asphalt mixtures containing a bio-asphalt derived from the fast pyrolysis of pine tree biomass (Mohammad et al. 2012). Attention was paid to rutting performance, water resistance, fatigue and low temperature cracking performance. Results were compared with the use of a conventional polymer-modified binder. It was noted that rutting resistance increased while on the other hand the fatigue resistance was reduced.

In the paper by Andersen field trials with vegetal oil based bitumen (partial replacement) in Norway demonstrating the applicability of the newly developed binder were described (Andersen et al. 2008). The study focused on the low temperature behaviour of both the HMA as well as the bio-binder. It was shown that the bio-binder was less temperature susceptible in comparison with a conventional soft binder and met all requirements of a soft binder.

Fini et al.discussed at length the rheological properties of a bio-oil modified binder in asphalt mixtures (Fini et al. 2010). Their study showed that especially the low temperature behaviour benefited significantly from the use of bio-oil due to the overall softening effect of the bio-oil. Other performance indicators such as fatigue resistance or water sensitivity were not probed for.

Yang et al. investigated the rheological behaviour of a bio-oil both used as a binder modifier or extender before and after short term ageing (Yang et al. 2013). Benefits were demonstrated with respect to increased rutting resistance and less temperature susceptibility as compared to unmodified binders.

In the paper by Lecomte the feasibility to use a vegetal clear binder (although polymer modified and therefore not entirely vegetal) to produce coloured asphalt mixes has been demonstrated (Lecomte et al. 2009). Some mechanical performance indicators such as ravelling or adhesive properties of the bio-binder were evaluated with satisfaction. However, road applications were limited to low traffic areas.

You et al. evaluated in detail the characteristics of different bio-oils and their impact on the performance of asphalt mixtures containing latter bio-binders (You et al. 2012). Generally, the use of bio-oils resulted in softer binders more prone to ageing as compared to conventional bituminous binders. An increased fatigue life was reported but mixtures were more susceptible to rutting (lower dynamic modulus).

Alerts

At present, there is very little information available with respect to the long-term performance and lifetime of bio-mass sourced binder pavements. In particular, test results as obtained from laboratory studies, which are validated in the field, are missing. Nevertheless, a risk for premature thermal cracking was observed in the field for some bio-binders (Baillié and Delcroix 2008). Latter phenomenon may be explained by the evolution with time of such binders (continuing polymerisation of constituents and/or greater susceptibility towards oxidative ageing as compared to bituminous materials).

In a lot of applications the bio-binder replaces partially (< 10 %) the conventional bituminous binder. Trials reported by Yang and co-authors indicated an incompatibility of bio-oils with the bitumen matrix when applied at high percentages (25 – 50 %). This resulted in phase separation and ultimately in binder instability (e.g. during storage).

Some bio-products are characterized by a lower thermal stability as compared to conventional binders and therefore special awareness is required.

6.2.3 Conclusions

Knowledge gaps

It is obvious from the current review that a large part of the literature deals with the performance of vegetal binders mainly in the laboratory both on a binder as well as a mixture level. Focus is given to the production stage of bio-binders, the corresponding asphalt mixtures, and their use in the field. No information however has been identified with respect to the user stage, the EOL (recycling) or possible benefits beyond the life cycle.

Alerts

Both alerts arising from external literature sources as well as raised by the reviewer during the sustainability assessment for vegetal binders were identified, the most important among them:

- It was observed by the reviewer that quite a lot of authors are tempted to claim common environmental benefits such as lower CO_2 emissions or energy use without providing any real data to substantiate latter statements. In this context, the flash pyrolysis process can serve as a good illustration, for which the amount of energy or transport needed to carry out latter process is very rarely commented on. This may hamper a correct overall evaluation of any particular ‘green’ material or process.
- Estimation of the exact scale of available raw material (feedstock) in order to guarantee a continuous supply to the end user is needed.
- Some thermo-chemical conversion processes of agricultural wastes may not only yield bio-binders but also possibly harmful or toxic waste (e.g. presence of PAHs). Latter is rarely accounted for in an overall assessment although it raises health and safety concerns.
- Incompatibility of bio-oils used as binder extender with matrix resulting in binder instability (e.g. during storage).
- Insight about the long-term performance and life-time of bio-mass sourced binder pavements is lacking.
- Some vegetal binders may evolve as a function of time possibly resulting in an increased risk of cracking. In other cases bio-products are characterized by a lower thermal stability as compared to conventional binders.

6.3 Sulphur extended/modified bitumen

6.3.1 Description

The concept of using sulphur as a bitumen extender/modifier has been around for three quarters of a century, but it was not until the 1970s that sulphur-extended asphalt has become available. However, the idea was not widely taken up because the cost of sulphur increased at that time, making this modifier uneconomical. Many of the reasons in the 1970’s for considering sulphur as an alternative binder source also exist today. Sulphur is currently expected to be in ample supply in the future, resulting primarily from tighter pollution abatement controls for gas emissions (SOx) from power plant stacks, sulphur contents in fuels and the greater exploitation of ‘sour’ crude oils.

Sulphur-extented bitumen has been used in asphalt mixture in several mass ratios ranging from 20/80 to even 50/50. Approximately 20 % of the sulphur can be dissolved and/or dispersed in the bituminous binder while the excess of sulphur (above ± 20 %) solidifies to a crystalline state and acts as a filler or stabilizer. The addition of about 30 % sulphur is common practice.

In the past sulphur was incorporated directly as a powder into the bitumen. However, such a process raised important health and safety concerns. In the late 1990’s a pelletized form of sulphur was developed (patented technology) overcoming most of latter concerns. The subsequent review deals with the use of this form of sulphur in asphalt pavements.

Worldwide, the use of pelletized sulphur is still limited. This is reflected in the relative small number of literature sources available and which are reviewed below.

6.3.2 Impact on sustainability

Global warming potential

Only in one paper by Nicholls (Nicholls 2011) an assessment was reported with respect to the carbon footprint of pelletized sulphur-modified asphalt mixture as compared to a conventional reference mixture. The approach included the raw material acquisition, its transport and processing and the subsequent asphalt production. In this evaluation the carbon footprint of sulphur-modified asphalt was 106 % of the reference mixture, although a typical asphalt production temperature of 135 °C is reported. This high percentage was attributed to the large transport distance between the pelletized sulphur production plant in Canada and its application in the U.K. It should be noted however that sufficient sulphur is generally available closer to the market (e.g. from oil refineries). In a scenario taking into account the potential to reduce pavement thickness (see also performance), a benefit could be demonstrated.

Alert

To the reviewer's opinion, the benefits of sulphur-extended bitumen reported in the literature with respect to global warming are too much emphasized. In the exercise discussed by Nicholls, one assumes that the impacts of the sulphur recovery at the refinery are zero because of environmental legislation (and therefore latter impacts are attributed to other products). Moreover, sulphur-extended binders are used to produce asphalt mixtures at about 130 °C. Therefore, latter process is presented as a warm mix technology (Conge et al. 2010, Nicholls 2011). However, such low production temperatures are needed in order to avoid possible harmful or toxic emissions (e.g. H_2S and/or SO_2). Despite taking into account both advantages, the balance remains rather negative.

Use of resources for materials

It is reported in the literature (Nazarbeygi and Moeini, 2012) that the use of pelletized sulphur contributes to a saving of bitumen corresponding to a partial replacement of about 30-35 w-%. It is also generally accepted that sulphur is currently available in huge quantities due to environmental restrictions with respect to sulphur content in a wide range of petroleum products.

Use of resources for energy

There was no detailed information found on the impact of pelletized sulphur used as extender/modifier for bitumen with respect to resources for energy.

Air pollution

There was no detailed information found on the impact on air pollution although it is generally stated in various communications that lower production temperatures while using sulphur-extended binders also results in lower emissions of particulate matter or other gases such as NOx, CO,…The issues related to the possible emissions of H_2S or SO_2 arising from the heating of sulphur-extended binders are discussed at length within the framework of health and safety.

Health and safety

In a majority of the literature sources one reports on the possible emissions of H_2S and SO_2 associated with the use of sulphur-extended binders reflecting the importance of health and safety issues. It is generally accepted that to minimize or even eliminate H_2S, product resulting from the chemical reaction between sulphur and bitumen, control of the asphalt production temperature is absolutely compulsory. A production temperature of about 130 °C is strongly recommended and a maximal temperature of about 145 °C should not be exceeded. It has been shown that while respecting latter temperature restrictions, the use of sulphur-extended binders in road pavements are complying with health and safety regulations in place (Conge et al. 2010, Nicholls 2009).

Alert

As indicated in a recent TechBrief of FHWA (Bukowski et al. 2012) and to the reviewer's opinion air pollution (and possible associated health issues, e.g. eye irritation) may also arise from airborn fumes and particulate (elemental) sulphur emissions (e.g. milling operations at end-of-life) since about half of the added sulphur is present in a separate crystalline phase. However, in contrast with H_2S or SO_2, specific environmental restrictions or regulations are currently often lacking. Moreover, questions were raised with respect to odour nuisance during the production and construction of asphalt pavements comprising sulphur-extended binders.

Financial cost

Nazarbeygi and co-author claim that the use of a sulphur extended binder at about 35 w-% can reduce the asphalt pavement production cost by about 25 % due to the abundance of sulphur at present (Nazarbeygi and Moeini, 2012).

Alert

Literature draws attention to the fact that using sulphur extended binders could reduce the cost of asphalt pavements. However, reviewers note that latter information was reported when the transport of the material was very limited. Moreover, this information is reflecting current economic situation. Latter may of course fluctuate significantly with time.

Recyclability

Several literature reports indicate the possibility to recycle RA containing sulphur-extended binders (Bukowski et al. 2012, Conge et al. 2010). However, both current environmental restrictions as well as health and safety issues render recycling at normal hot mix temperatures impossible due to increased emissions of H_2S and SO_2. Therefore, only cold recycling processes can be envisioned. Using latter techniques, the percentages of RA will be limited (< 30 %).

Alerts

To the reviewers opinion the necessity to identify sulphur-extended asphalt pavements before milling operations are carried out (lack of traceability) will further hamper or limit its recycling potential. Any mistake (even accidental) in this context could jeopardise the future use of sulphur-extended binders.

Performance

Much research has already been conducted on the use of sulphur-extended binders in asphalt pavements with respect to design, material properties, construction and the evaluation of performance. There appears to be significant evidence that asphalt mixtures comprising sulphur-extended binders provide performance equal or even better to conventional AC mixtures (Nicholls 2009, Nazarbeygi and Moeini, 2012, Bukowski et al. 2012). It is generally accepted that the use of sulphur-extended binders results in asphalt mixtures characterized (in laboratory) by an increased stiffness, improved Marshall stability and higher resistance to rutting. The water sensitivity, the low temperature fracture properties and fatigue behaviour are only affected to a minor extent. Moreover, the follow up of field trials also confirms a quite similar behaviour as reference mixtures as no (premature) distresses are observed.

6.3.3 Conclusions

Knowledge gaps

There is at present limited information available about the recycling potential of sulphur-extended pavements. Although it is acknowledged that possible harmful emissions are inhibiting a classical hot recycling process, an extensive study demonstrating the feasibility and the economic viability of (cold) recycling such pavements is lacking. It should also be noted that the current site experience with pelletized sulphur as binder extender or modifier is limited to a few countries in the world such as US, Canada, China or in the Middle-East.

Alerts

Both alerts arising from external literature sources as well as raised by the reviewer during the sustainability assessment for vegetal binders were identified, the most important among them:

- It is the opinion of the reviewer that the carbon footprint of pelletized sulphur extender is underestimated since elemental sulphur is not accounted for during the refinery of crude oil (allocated to other products). This could alter the overall sustainability assessment.
- There is too little attention paid at present to the health and safety issues related to the particulate (dust) emissions of elemental sulphur. Latter may also be of importance during the recycling of such materials at EOL.
- The maximal handling temperature of sulphur-extended binders is about 145 °C (recommended temperature 130 °C) in order to avoid harmful releases of gases. This limits strongly its full recycling potential and creates always a potential risk for accidental emissions.

6.4 Polymer modified bitumen (PMB)

6.4.1 Description

The use of polymer modified bitumen (PMB) is widely spread throughout Europe for road applications already for a long time (since 1980's). In that sense, it is debatable if PMB should be labelled as new green materials. However, to the opinion of the authors, the impact of PMB on the durability and therefore on the overall life time expectancy of an asphalt pavement is thought to be so high that considering latter materials is required. Moreover, the discussion on the addition of polymers can serve as a reference case for the application of many other additives in the field (see chapters 2 and 7).

At present, PMB represent about 10 % of the total bitumen consumption in Europe (Eurobitume 2013). In some countries the market share may be as high as about 25 % (EATA 2012). Over the years, a broad range of polymeric additives has been used to modify bitumen (Read and Whiteoak 2003). The most common types used include either thermoplastic elastomers such as styrenic block copolymers or plastomers such as polyolefins or ethylene vinyl acetate (EVA). At present, the most common polymer type in Europe is styrene butadiene styrene (SBS) in its granular form. Typical SBS polymer content is around 3.5 w-%. The production of latter PMB includes a high shear mixing step at elevated temperatures in order to obtain the appropriate polymer distribution. In the EU, PMB comply to the product standard EN 14023.

In the literature, an overwhelming amount of information is available about the mechanical performance benefits of PMB (see paragraph on performance). However, detailed data within the framework of life cycle assessment is rather scarce. It is noted that benchmarking with paving grade bitumen is rather common practice while discussing PMB.

6.4.2 Impact on sustainability

Global warming potential

By far the most detailed report with respect to the eco-profiling of bituminous binders used in Europe has been published recently by Eurobitume (Eurobitume 2011). The report provides a life cycle inventory (LCI) of both paving grade bitumen as well as PMB (based on 3.5% of SBS). The bitumen LCI is a cradle to gate study. Moreover, the allocation between bitumen and other co-products made from crude oil is based on mass balance at the extraction and transport stages, while at the refining level this allocation is based on relative economic values. Where possible primary data sources have been used, but where not available information was retrieved from the eco-invent database. It should be noted that this LCI study is a phase preceding a life cycle assessment (LCA) and that data allocated in the LCI overview should serve as input in a LCA exercise.

Taken into account the remarks stated above, it is clearly demonstrated that the addition of SBS polymer augments by about 50 % the CO_2 emission as compared to a paving grade bitumen (to about 350 kg CO_2/tonne of bitumen). Latter increase is of course due to the production of SBS itself, but also arising from the high shear mixing process while mixing the SBS granulates into the base bitumen. Furthermore, the increased viscosity of PMB binders necessitates higher handling and storage temperatures (in the range of 15-20 °C) as compared to conventional binders. However, it should be noted that latter effects could be outweighed by a longer life time of the corresponding asphalt pavement while conducting a complete LCA analysis.

More recent publications by Butt and co-authors (Butt 2012) substantiate the above discussed data. Moreover, authors assumed that the application of a PMB results in an increase of 17 % in fuel consumption while producing the asphalt mixture at higher temperatures in order to compensate for the increased viscosity of the binder (Butt et al. 2014).

Alert

To the reviewer’s opinion, the environmental impact of the use of additives (e.g. polymeric materials) is generally poorly documented. Probably, due to this lack of information the negative ecological effects accompanied by their use are underestimated.

Use of resources for materials

There was no detailed information found on the impact of the addition of polymers such as SBS on the use of resources for materials in the literature. Of course, in order to produce SBS the given amount of monomeric components (styrene and butadiene) needs to be retrieved from the refinery process of crude oil and therefore uses a certain quantity of primary materials as well.

Use of resources for energy

The consumption of energy sources involved for the production of both a PMB as well as a paving grade binder has also being described in the LCI report of Eurobitume. In particular, significant increases are allocated in case of a PMB binder for the consumption of natural gases (more than double), crude oil and coal. These figures are in line with the CO_2 emissions discussed above.

Alert

It is important not to confuse at any time energy resources used for processing (e.g. bitumen, SBS,…) and energy resources used as raw material (= feedstock energy). Latter is potential energy embedded in the bitumen as such (calorimetric value), but does not result in emissions of greenhouse gases as long this energy content is not lost. Since latter potential is quite high in case of bituminous materials, it is essential to fully understand the system boundaries of any study reported in order to facilitate a correct interpretation of data.

Air pollution

In analogy with the global warming aspect for PMB binders, substantial increases are allocated in the LCI study of Eurobitume to emissions to air for other components such as SO_2, NOx VOCs and particulates.

Health and safety

As the use of PMB is already well established over the years appropriate information with respect to the known health, safety and environmental hazards of such materials has been made available by the producers through Material Safety Data Sheets (MSDS) to the customers. Moreover, it should be noted that bituminous binders have been registered within the REACH (Registration, Evaluation, Authorization and restriction of Chemicals) framework

(Leroy and Carré 2010). No further information related to polymeric additives could be identified in the literature.

Financial cost

The cost of bituminous binders is generally not discussed in the public domain. Nevertheless, based on reviewers information a current price in West-Europe for bitumen amounts to about 400-500 EUR/tonne. Since a cost of 3 EUR/kg can be associated with the use of SBS, the resulting PMB constitutes an additional cost of around 100 EUR/tonne (20 % increase as compared to a paving grade binder). Latter additional cost may influence the cost-effectiveness of PMB.

Alert

The above cited information reflects the current economic situation and depends on geographic location. Latter may of course fluctuate significantly with time.

Recyclability

Reclaimed Asphalt (RA) comprising a PMB is generally considered not to be any different from conventional RA containing unmodified bitumen in term of its 100 % recyclability. On the other hand, experience in many European countries is very limited since most of the PMB containing pavements are recently constructed and not up for recycling yet. One estimated in 2011 the fraction of RA comprising a PMB binder to be around 2 % of the total amount of available RA.

Very few studies investigated the possible full recycling potential of RA comprising PMB by valorising latter material back into surface layers and therefore make use once again of the enhanced binder properties of the aged PMB. In this context, a study carried out by TRL which reports on the possibilities and limits of such an approach is very worthwhile mentioning (Carswell et al. 2005). Positive field experiences gained from this research have recently resulted in a best practice guide for recycling into surface courses (Carswell et al. 2010).

Alerts

Within the framework of the Re-Road project some countries like Belgium and Germany reported the occurrence of sticking problems using parallel drum technology while recycling RA containing PMB (Nielsen in Re-road project Deliverable 4.2 2011). Possible solutions to this particular problem include the cold addition of RA (although limiting the recycling potential to about 20 %), an optimization of the design of the parallel drum used (Paramix project Deliverable 5.3 2004) or limiting the fraction containing PMB to about 1/3 of the total amount of RA by diluting with regular RA.

In the Netherlands the road administration has imposed the use of a conventional paving grade binder for porous asphalt surface layers on their motorway network being aware of existing problems while recycling RA containing a PMB binder and this despite the poorer life time while doing so.

Performance

The main benefits of using PMB have been documented extensively in the literature. It is considered beyond the scope of this report to discuss in detail latter data. Therefore, authors like to refer the reader to a number of available literature sources (and reference therein) dealing with the enhanced mechanical properties of both PMB as well as their corresponding asphalt mixtures (Read and Whiteoak 2003, European BITspec seminar 2003, Partl 2003, Robinson 2004, Nicholls 2006). Latter include both an increased performance at high temperatures (increased resistance to permanent deformation) as well as low temperatures (resistance to cracking). Furthermore, the advantages with respect to fatigue cracking and ravelling have been demonstrated.

Moreover, in the currently ongoing CEDR project FunDBits (Functional Durability-related Bitumen Specification) new internationally available data is reviewed in order to develop performance-based bitumen characteristics which may be introduced into the European bitumen product standards. The project builds on the knowledge already gained in the BitVal project (Nicholls 2006) and will address data published from 2006 onwards. Obviously, the output of FunDBits will serve as a source of relevant information for evaluating performance issues of PMB.

6.4.3 Conclusions

Knowledge gaps

Although PMB are widely used in asphalt mixture for surface layers and their mechanical performance is very well documented, data reported in the context of a full LCA assessment is very scarce (as for many other additives). It is recognized however that the LCI report published by Eurobitume may serve as a very useful start for such evaluation.

It is unclear at present to what degree one can recycle RA containing PMB in order to exploit to a maximal extent the possible residual added value of latter type of RA. Further studies investigating the feasibility of such an approach both on a mechanical performance as well as an economic level should be conducted.

Alerts

Both alerts arising from external literature sources as well as raised by the reviewer during the sustainability assessment for polymer modified bitumen were identified, the most important among them:

- It is the opinion of the reviewer that the carbon footprint of additives such as polymers is underestimated and that more data are needed to fully comprehend their impact, although their use might be justified taking into account the increased durability of asphalt mixtures comprising PMBs.
- Although asphalt mixtures are considered 100% recyclable, problems during the hot recycling of RA containing PMB have been reported limiting its full recycling potential.

7 Additives

7.1 Introduction

Several types of additives are introduced in asphalt mixtures either to improve their mechanical performance (e.g. decrease water sensitivity) as well as other characteristics such as resistance to segregation before compaction, the colour of pavements or the potential of an increased use of RA by rejuvenating the aged binder. Numerous types of additives are currently available on the market. Their use is generally incentivized if the improvements obtained thanks to their use result in a reduction in the consumed energy and emissions in the whole life cycle compared to the traditional mixture (Butt 2012), or in an increased safety for the road users.

This paragraph aims to give an overview of the commonly used additives such as anti-stripping agents, pigments, fibres and rejuvenators, excluding additives intended for warm mix asphalt which are covered by §2.2 and 2.3)

In general few literature reports are available on the environmental effects of asphalt additives and comparative studies still have to be published (Butt et al. 2014). Although additives constitute a relatively small part of asphalt mixtures, their environmental impact should not be underestimated (see also discussion on SBS polymer in §6.4.2) and should therefore be evaluated more closely.

7.2 Anti-stripping agents

7.2.1 Description

Anti-stripping agents are liquid or dry materials added to the asphalt mixture in order to minimize the stripping of the bitumen from the aggregate. The stripping is attributed to the greater affinity of the hydrophilic aggregate surface for water than for bitumen. In the presence of water, this behaviour leads to the loss of adhesion between the aggregate and binder and consequently to distresses such as ravelling, cracking (due to water infiltration and multiple frost-thaw cycles) and localized failures (potholes) of the asphalt pavement.

Preventive measures such as the introduction of anti-stripping agents are taken in the mixture design phase in order to reduce moisture sensitivity. The agents used to achieve a durable bond are commonly divided in two categories: agents added to the bitumen and agents added to the aggregates. The first category consists of chemical products commonly referred to as liquid anti-stripping agents (amine functionalized chemicals). The second group refers to dry additives such as hydrated lime or Portland cement. Waxes, polymers, sulphur, anti-oxidants, rubber and carbon black can also act as anti-stripping agents (Aksoy et al. 2005). Chemical interfacial reactions are believed to underlie the interaction between additive and the bitumen-aggregate system (Epps et al. 2003).

In the chemical industry amine compounds are derived from ammonia. Examples include tallow diamine, polyamines based on bis-hexamethylene triamine and amidoamines of different carbon chain length. They are used to reduce the surface tension between the aggregate surface and the binder improving the wettability of the surface. The hydrocarbon chain bonds with the bituminous matrix while the amine groups react with the aggregate surface creating a bridge between the aggregate and the binder (Little and Jones 2003).

Amines are added in small quantities to the hot bitumen, typically in the order of 0.25 to 0.75 w-% (to the binder).

Hydrated lime is widely used in North America and Europe. The general practice is to add 1 to 2.0 % of lime by the dry weight of the aggregate to the mix, depending on the gradation curve. Hydrated lime can also be added indirectly during the asphalt mixture production by the use of fabricated fillers containing up to 25 w-% of hydrated lime resulting in similar concentration of hydrated lime. Hydrated lime reacts with both aggregates and bitumen: in the first case altering the surface charge and therefore improving the acidity balance of the aggregates in parallel reacting with some of the (acidic)functional groups of the bitumen (Putman and Amirkhanian 2006, Little and Jones 2003).

Differently from hydrated lime, the use Portland cement decreased significantly in the last two decades reducing the research on its effects on moisture sensitivity of asphalt mixtures. Its dismissal could be connected with high costs and its reactivity with water, but no literature on the topic was found.

7.2.2 Impact on sustainability criteria

Global warming potential

The impacts of the use of additives on global warming are to a large extent related to their production. Lime is a product derived from limestone in an industrial process. Naturally occurring limestone or calcium carbonate ($CaCO_3$) is transformed to quicklime (CaO) by applying a high amount of heat. When slaked with water, hydrated lime is formed. An independent reviewed LCI datasheet for quicklime has been published in 2011 (EESAC 2011). In this report, a GWP impact of 1.1 tonne CO_{2e} per tonne of quicklime is stated.

The overall effect on the global warming potential is however questionable. A comparative LCA study for a HMA surface layer showed that the addition of 1.5 % of hydrated lime would lead to 23 % lower GHG emissions compared to a HMA without hydrated lime (see **Figure 7-1**, Shtiza 2014). Although the study promises great results, the reduction of CO_2 can mostly be attributed to the assumption of a 20-25 % longer service life (and consequently reduced maintenance) of the HMA containing hydrated lime. This assumption is made at the beginning of the study and should be validated.

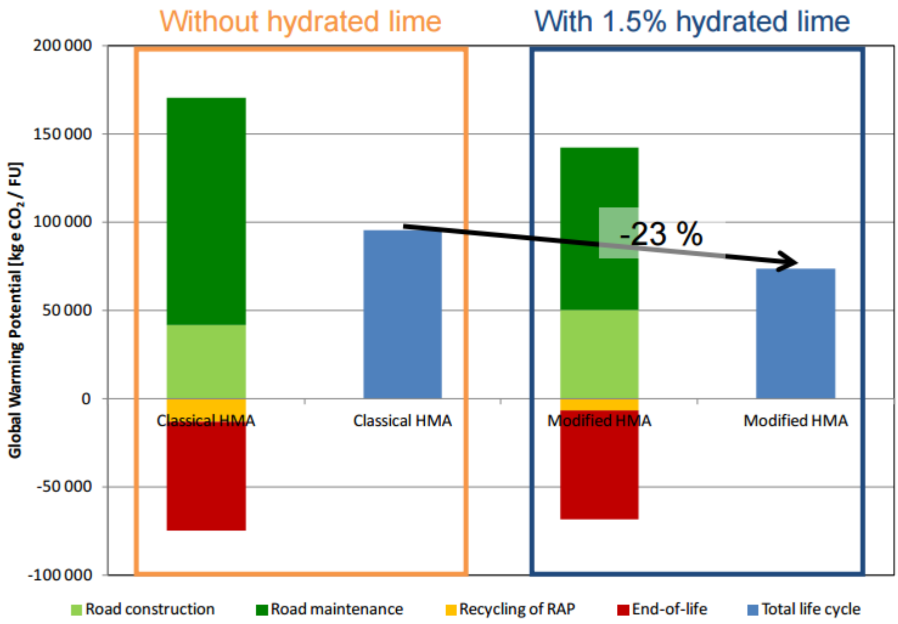


Figure 7-1 Reduction of the global warming potential between HMA with and without the addition of hydrated lime.

(from Shtiza 2014)

In 2012 Leon (Leon & Jensen 2012) published on some of the LCA parameters for a WMA chemical additive called Cecabase RT. Although, this particular additive is to be used in the framework of WMA technology, its chemical nature is very close to a liquid anti-stripping additive produced and supplied by the same chemical company. Therefore, the above mentioned data is a fair indication of the environmental impact of anti-stripping additives. In the publication by Leon, a GWP of 4.32 tonnes of CO_2 is associated with the production of 1 tonne of the additive. Consequently, this high figure results, even when used in small quantities (below 1 w-% to the bitumen) in a substantial increase of the GWP value of an asphalt mixture (in case of WMA while applying 0.4 % of the additive, about 25 % of the advantage in terms of GWP was lost by the production of the additive). Although, these numbers are related to one particular additive, it is the reviewer's opinion that similar figures apply to other chemical engineered additives.

Use of resources for energy

Because of the high temperatures required during the production of quicklime and consequently hydrated lime, a primary energy demand of 5.4 MJ/tonne of quicklime is stated in the paper of Schlegel et al. (2015).

In the same paper by Leon et al. (Leon 2014) an energy demand for the production of the WMA additive similar to a liquid anti-stripping additive of about 80 MJ/tonne of additive is reported.

Use of resources for materials

Being dry additives considered active filler, they partially replace any other filler type used in the mixture. Without affecting the total consume of materials as in the liquid additives case.

However, since their purpose is to improve the adhesion between aggregates and bitumen, their use could promote the use of local, less valuable, materials.

Air pollution

No information could be identified with respect to the air pollution of anti-stripping agents. But the use of local materials could reduce the transportation between the quarry and the asphalt plant, and consequent air-born emissions.

Health and safety

Although amines are used in very small concentrations, contaminants released at high temperatures (amines are recognized to be sensitive to oxidation and thermal degradation above a critical temperature threshold) have been considered partially responsible for long term health issues of asphalt workers. Low molecular polyamines and alkanol polyamines, present in the liquid anti-stripping additive are known to cause eye and respiratory tract irritation and skin sensitization (Levin and Järvholm 1999).

Financial cost

Use of anti-stripping agents will increase the production cost of asphalt to some extent. However, the small amounts of additives necessary will make the additional cost relatively small (about 1 EUR/tonne asphalt). On the other hand, according to some U.S. road administrations, a 25 % increase in durability is expected compared to not lime treated pavements (Hicks et al. 2003), hence reducing the overall long-term cost for the road owner.

Recyclability

Use of anti-stripping agents has very little impact on recyclability. Dry additives as hydrated lime and cement will constitute the inerts of the future RA while most of the amines have been found to easily degrade when in freshwater (Eide-Haugmo et al. 2009).

Performance

The positive impact of the use of hydrated lime on the durability of asphalt pavements has been highlighted extensively in literature. A recent review of Lesueur (Lesueur 2010) provides an excellent summary of the state-of-the-art with respect to the world wide use of hydrated lime as additive in asphalt mixtures. In particular, by enhancing the water damage resistance, anti-stripping additives can increase the service life of the pavement reducing maintenance, resurfacing needs and the consequent raw material needs.

For some types of aggregates (such as river gravel) the service life will be reduced significantly without proper anti-stripping agents. As described in the previous paragraph, anti-stripping additives promote the adhesion between aggregate and bitumen reducing the susceptibility of the mixture to moisture and therefore guaranteeing safe driving conditions for extended periods of time (Little and Jones 2003, Hao and Liu 2006, Aksoy et al. 2005).

7.2.3 Conclusions

Knowlegde gaps

Anti-stripping agents are needed to improve the performance of asphalt pavement and reduce the maintenance and resurfacing needs. Since the moisture damage process itself is not yet completely understood, difficulties have been encountered in defining the entity of the enhancement due to the use of anti-stripping agents. Questions about the affinity between additives and bitumen/aggregates, the quantities to be used, the mixing techniques and many other issues have not yet been answered.

Alerts

Although it is anticipated that high quantities of CO_2 are released during their production, the large extension in terms of pavement life will probably not increase the total emissions associated with the entire pavement life cycle. However, for a large majority of the additives, no reliable data with respect to their sustainability impact are reported at present.

7.3 Pigments for coloured asphalt

7.3.1 Description

Coloured asphalt is mainly used for aesthetic purposes or to separate different types of traffic (e.g. red for bicycle lanes, yellow for pedestrians,…). Making asphalt surfaces lighter and more reflective could also improve visibility and reduce the asphalt temperature and the air temperature close to the road.

Synthetic inorganic pigments are preferred for coloured asphalt, because of their thermal stability and purity (Pierard et al 2013). Transition metals are responsible for colour in inorganic pigments and metal oxides and oxide hydroxides are particularly important because of their optical properties, low price and availability (Buxbaum et al 2005). Red brown and yellow iron oxides, green chrome oxide and white titanium oxide are the most commonly used pigments in coloured asphalt.

The pigment contents depend on the desired asphalt colour, the colour of the aggregates and the nature of the binder. Percentages vary from 3-4 % by mass with classical black or pigmentable bitumen, to 1-2 % with light-coloured binders (Pierard et al 2013).

7.3.2 Impact on sustainability criteria

Global warming potential

Without going into the production processes, described extensively in (Buxbaum et al. 2005), the Titanium Dioxide Manufacturers Association has determined a cradle-to-gate carbon footprint calculation of the manufacturing processes for titanium dioxide products, yielding 5.3 $tCO_{2e}/tTiO_2$ product (TDMA 2013). This value is also confirmed in (VDMI 2012). This implies that if only 1 % of pigment is used, the carbon footprint of asphalt (typically less than 100 kg CO_{2e}/t) almost doubles, only due to the pigment production carbon footprint. In combination with the use of synthetic binders, the total carbon footprint is even higher due to the production process of these binders. This large increase in carbon footprint has to be weighed against the advantages of using coloured asphalt.

The use of pigments often requires the use of coloured aggregates to support the colour, which implies longer distances from the quarry to the plant, resulting in more CO_2 emissions and energy consumption.

However, in the use phase, there may be a positive effect on GWP associated with the reduction in energy consumption. This is further explained in the following point.

Use of resources for energy

The production process of pigments is an energy consuming process. Considering also the need of special binders and aggregates for the production of coloured asphalt, it is clear that coloured asphalt will obtain a very weak score for energy consumption in the production stage, when compared to black asphalt.

In the use phase however, there may be some positive effects on the energy consumption (and consequently also on GWP), depending on the location of the coloured asphalt:

- Higher reflectivity of asphalt pavements can be exploited in terms of better visibility during night time or in tunnels, thereby reducing lighting needs.
- Reduction of the heat island effect associated with higher albedo levels of the flat surfaces could induce a decrease in the use of air conditioning during hot periods (Error! eference source not found. **Figure 7-2**).

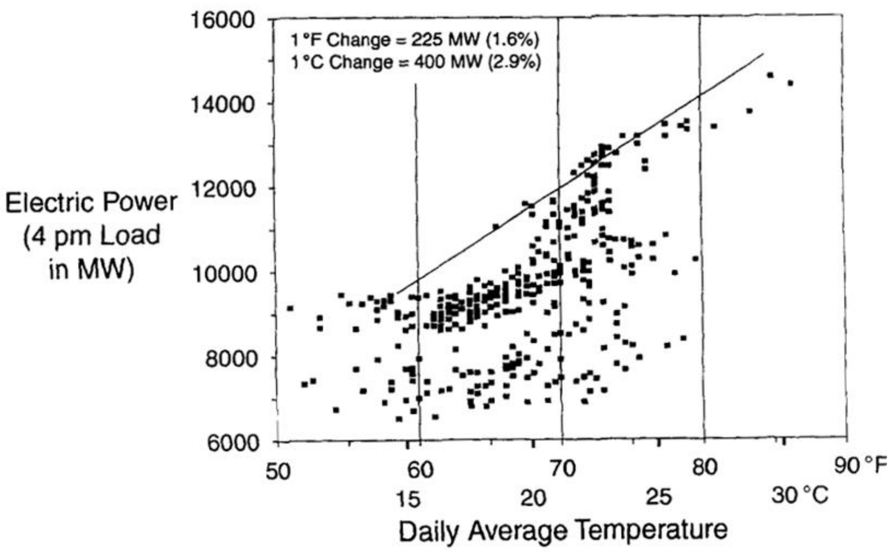


Figure 7-2 Electric power supplied by the Southern California Edison (LA) utility at 4pm, as a function of the average temperature in 1988

(from Pomerantz et al. 1999)

- Coloured asphalt in urban areas (e.g. for bike lanes or pedestrian crossings) creates higher awareness of potential conflicts between different types of road users and therefore improves traffic safety. This may encourage the use of softer modes of transport rather than cars and will indirectly decrease the fuel consumption by traffic in the use phase.

Use of resources for materials

The use of coloured asphalt has an impact on the use of resources for materials:

- Coloured asphalt often requires the use of translucent binders, such as vegetal or synthetic binders (see chapter 6).
- Coloured asphalt increases the demand for particular aggregates that support the colour of the asphalt.
- Pigments partially replace the filler, but in coloured asphalt, special white virgin filler is needed to enhance the colour.
- To our knowledge, reclaimed asphalt has not been used in coloured asphalt.

Air pollution

Air pollution during pigment production is highly regulated.

The addition of pigments for the production of coloured asphalt normally is not expected to have an impact on air pollution.

In the use phase, there may be a positive effect on air pollution, as shown by Pomerantz et al. (1999), who studied the impact of reflective pavements on the environment. Their study observed that when the temperature rises, it is more likely to exceed the maximum levels of smog concentration (see **Figure 7-3**). Among the effects of reduced air temperatures, they listed: decreased need for cooling energy, generating capacity and thus less emissions from power plants; some photochemical reaction rates of smog production decrease; temperature-dependent biogenic hydrocarbon emissions slow down, and evaporative losses of organic compounds from mobile and stationary sources are reduced.

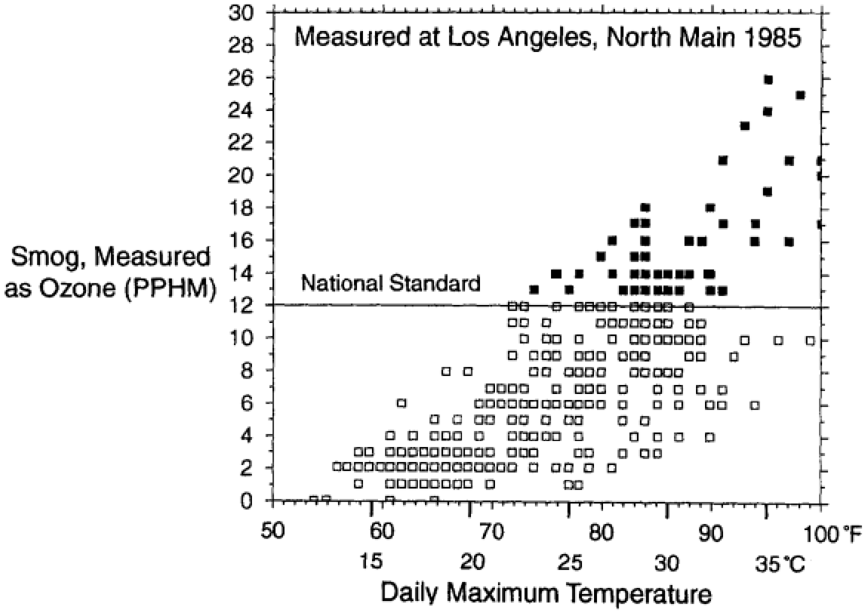


Figure 7- 3 Maximum ozone concentration in LA as a function of the daily maximum temperature, for every day in 1985
(from Pomerantz et al. 1999)

Health and safety

No evidence was found of negative effects on asphalt workers health from using coloured asphalt. The volume of this type of asphalt is relatively limited and long term effects would probably not so easily be discovered.

Nevertheless, toxic materials could be used in the pigment production and lead to increased incidence of diseases as observed among employees in companies producing chromate pigments (Langård & Norseth 1975, Yoshioka & Takeoka 2014). Per pigment category the H&S issues are discussed extensively in (http://vdmi.de/files/saf-p-en.pdf).

Clear binders used for coloured asphalt may also have negative effects (see chapter 6).

A positive effect of the use of coloured asphalt is the increased safety for pedestrians and cyclists, especially in urban areas. Visible separation of the areas for cars and pedestrians/cyclists makes it safer and encourages the road user to travel by bicycle or by foot, rather than by car. This also has an indirect, but positive effect on the carbon footprint in the use stage, as previously mentioned.

Financial cost

The cost of pigments, clear binders and coloured aggregates increases the price of the asphalt considerably compared to black asphalt. A rough estimation of the price of red coloured asphalt concrete compared to black asphalt concrete (BRRC 2006), gives an increase of:

- 70 % in the case of normal aggregates and pigmentable bitumen
- 140 % in the case of normal aggregates and synthetic binder
- 80 % in the case of coloured aggregates and pigmentable bitumen

- 150 % in the case of coloured aggregates and synthetic binder
- 230 % in the case of coloured aggregates and synthetic binder,

In the case of green, yellow or white asphalt, prices can even double or triple.

Moreover, especially when only small quantities are produced, the production and construction costs also increase due to the need of extensive cleaning of the equipment (plant equipment, finisher, compactors, …) after producing and laying normal black asphalt.

Recyclability

The cost of recycling in surface courses of the same colour would be higher, because of the need for separate milling and storage for recycling in coloured asphalt. Recycling in base layers could be considered as an alternative solution, but this implies downgrading of the asphalt.

In any case, compatibility of the recycled binder and the new binder is an important issue that shall be considered.

Performance

The impact of the use of pigments on performance depends on the mix design. The mix design has to be optimized as function of the specific characteristics of the pigment, particularly the mass density and stiffening effect, which are both very high compared to a natural filler. Provided the mix formula is properly adapted as function of these characteristics, one may assume that the impact on performance is limited (Piérard et al 2013). According to some studies, pigments may have an influence on the adhesion between binder and aggregates, and consequently on water sensitivity of the mixture.

On the other hand, research at BRRC showed that there is a significant influence of the binder on the performance of coloured asphalt.

The effect of pigments, specific binders and aggregates on the performance of coloured asphalt makes performance testing as part of the mix design essential for a coloured mix, but if the asphalt mix is properly designed as function of traffic conditions and climate, the performance of coloured asphalt can be more or less equivalent to the performance of black asphalt.

In a French trial project (Sint-Jacques 2006), it was demonstrated that the lower surface temperature of lightly coloured asphalt, when compared to black asphalt (up to 5°C in the trial project), is also beneficial to reduce rutting.

7.3.3 Conclusions

Pigmented asphalt surfaces could beneficiate the road users with better visibility, increased safety and lower surface temperature. However, higher costs, financially and from the ecological viewpoint, discourages their extended use.

7.4 Fibres

7.4.1 Description

The main purpose of adding fibres to an asphalt mixture is to prevent mix segregation (binder drainage) during storage and transport to the worksite: the fibres significantly stiffen the mortar at high temperatures reinforcing the binder phase. A stiffening effect on the mortar at in-service temperatures can be observed in some cases (Brown et al. 1996). Natural and synthetic fibres such as cellulose and polyester have been widely used in the asphalt industry (Wu et al. 2007). Mineral fibres as rock wool are also used in asphalt pavements and are sometimes preferred over cellulose since organic fibres can absorb water leading to premature moisture damage (Chowdhury et al. 2006). However, already in 1963 the use of recycled fibres from automobile tires and carpets was introduced (Thodesen 2008).

7.4.2 Impact on sustainability criteria

Global warming potential

Use of fibres has very little impact on the global warming potential.

Use of resources for energy

Use of fibres has very little impact on the use of resources for energy.

Use of resources for materials

The tire processing industry and the automotive carpet industry produce in fact great quantities of waste cellulose and polyester fibres whose disposal is a large economic and environmental problem. Their use as reinforcing material for asphalt pavements does not only provide a solution to the disposal problem but also reduce the production of fibres manufactured for this specific application.

Air pollution

Use of fibers has very little impact on air pollution.

Health and safety

Use of fibers has very little impact on health and safety.

Financial cost

The use of fibers can potentially be beneficial to the total cost of the road materials. Being them considered as inerts in the design process, their use could correspond to a reduction of the costs of raw materials.

Recyclability

Use of fibers has very little impact on recyclability of the pavement itself but will give a second life to tires and carpets.

Performance

Fibres are used in asphalt mixtures as a stabilizer to prevent binder's drain down in open-graded mixtures (Hansen et al. 2000). However, effects on moisture sensitivity, pavement deformation, ageing, fatigue and thermal cracking resistance have been observed for some types of fibre (Lee et al. 2005, Kaloush et al. 2010). Improvements in terms of toughness of the mixture containing tire and carpet fibres compared to cellulose are also described by Kaloush et al. (2010).

7.4.3 Conclusions

Alerts

Although the use fibres can prevent draindown of the bitumen and allows a controlled disposal of large quantities of waste, several negative effects on the pavement performance have been observed.

7.5 Rejuvenators

7.5.1 Description

Rejuvenators are engineered cationic emulsions containing maltenes and saturates that have to satisfy several requirements for viscosity, flash point, volatility, compatibility, chemical composition and specific gravity (ASTM, 2010). Lube extracts (highly naphthenic or aromatic fractions extracted from lube stock) and extender oils (aromatic oils also extracted from lube stock) are used as rejuvenators.

Rejuvenators are capable to restore physical and chemical properties to the aged binder (Karlsson & Isacsson 2006). Therefore, rejuvenators are added to asphalt mixtures containing a high percentage of reclaimed asphalt.

According to Zaumanis et al. (2013b), rejuvenators should rapidly diffuse into the reclaimed asphalt (RA) mobilizing the aged binder hence facilitating the workability of the mixture in the short term; while in the long term they are required to reconstitute the chemical and physical properties of the aged binder and guarantee their stability for the service period.

Karlsson and Isacsson (2006) report about previous experiments that investigate the diffusion of rejuvenators into aged bitumen: first the rejuvenator forms a very low viscosity layer surrounding the bitumen coated aggregate; afterwards it starts to penetrate into the aged binder layer, decreasing the amount of raw rejuvenator surrounding the aggregate and softening the aged binder itself; then, when no raw rejuvenator remains, the penetration of the rejuvenator continues, decreasing the viscosity of the inner layer and gradually increasing the viscosity of the outer layer; after a certain time, equilibrium is approached over the majority of the recycled binder film. **Figure 7-4** shows the penetration values at 25°C for each layer as the outer and inner layers approach the same consistency in the days following the mixing as recorded in the same experiment.

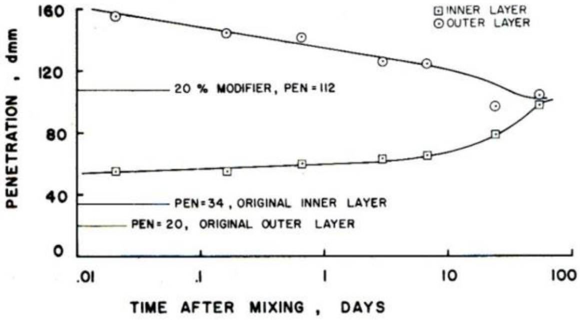


Figure 7- 4 Penetration of the outer and inner layers during diffusion
(from Tran et al. 2012)

7.5.2 Impact on sustainability criteria

Global warming potential

Being lube extracts derived from the distillation of crude oil, their impact on global warming potential is related to the refinery emissions and the quality of the oil (Karras 2010).

Use of resources for energy

Large use of energy in the production phase derives from the oil distillation (Karras 2010) and in lower scale from the extraction of naphthenic and aromatic fractions and, extender oils. No specific information on the required energy could be found in the literature.

Use of resources for materials

Research on RA aims to a 100 % use of recycled pavements. In order to achieve this goal in the future, rejuvenators are a key factor.

Existing asphalt pavement materials are commonly removed during resurfacing, rehabilitation, or reconstruction operations. Once removed and processed, the pavement material becomes RA, which contains valuable asphalt binder and aggregate. The use of RA in HMA can have a large economic, environmental, and engineering impact in pavement recycling (Copeland 2011). However, low percentages of RA, less than 25 % by weight of aggregate, are allowed by most highway agencies (Tran et al. 2012). The main obstacle to high RA usage is the aged binder: in order to resist to cracking or fracture, the binder should be able to stretch without breaking or more specifically, the asphaltenes should be able to flow within the binder. Over time changes in the chemical composition of the binder transforms some of the maltenes into asphaltenes, resulting in a lower dispersion of the latters that will tend to flocculate increasing the viscosity and lowering the ductility of the binder (Tran et al. 2012). In order to restore the binder's properties and make the bitumen contained in the RA available to the new mix, rejuvenator agents are used.

Alert

The effectiveness and limits of rejuvenators for such purposes have not yet been demonstrated in sufficient detail.

Air pollution

Effects of the use of rejuvenators on air pollution are related to the crude oil quality that determines the amount and type of emissions during the refinery process (Karras 2010).

Health and safety

There are no negative impacts on health and safety reported in the literature. Possible worker's health risks related to heating of asphalt or presence of coal tar in reclaimed asphalt should be taken into account (Karlsson and Isacsson 2006), but these are alerts related to the use us RA in general.

Financial cost

The use of rejuvenators implies larger amount of RA used in road construction. It is therefore associated with reduction of costs in terms of raw materials, transport and production: based on a cost comparison, 50 % RA mix with rejuvenator can provide cost savings of approximately 29 % compared to the cost per ton of virgin mix (Tran et al. 2012).

However, high initial costs, including the purchase of adequate equipment, the repurposing of asphalt plants and training of employees should be considered.

Recyclability

Use of rejuvenators does not increase the potential for future recycling of RA pavements since more chemicals would be needed to re(re)activate the binder as suggested by Chen et al. (2009). However, the same study recommends limiting to 40 % the reuse of RA to make a second RA because of higher possibility of moisture induced damage.

Performance

The rejuvenators' purpose is to reactivate the original bitumen present in the old mixture in order to improve the asphalt performance. Episodes of over-softening of the binder and consequent propensity to rutting damage have been reported (Shen et al. 2007) while low temperature improved performance has been observed by Zaumanis et al. (2013a). Moreover, the reclamation process may also contribute to the inhomogeneity of the recycled pavement material (Karlsson and Isacsson 2006).

7.5.3 Conclusions

Knowledge gaps

Although rejuvenators are widely promoted and used to increment the RA content in asphalt mixtures, there is at the present limited information about their impact on sustainability.

8 General conclusions

The review of the knowledge and information related to the sustainability of new materials and technologies in the domain of bituminous mixtures has shown that there are still many knowledge gaps, despite of the fact that some of these techniques have been in use for many years and are nowadays common practice.

The information is often limited to one stage in the life cycle where the most notable gains can be demonstrated (usually the production stage). The reader should be aware that these gains can be partly or totally lost in another stage (e.g. the production of raw materials or transport). This is the reason why it was decided that the methodologies developed within EDGAR have to cover the complete life cycle from cradle to grave.

Regarding the main categories of criteria that were considered, the following general conclusions can be drawn:

- *Global warming potential* is one of the best discussed impact categories in literature. For bituminous mixtures, GWP can be mainly attributed to the processes of extraction/production of the raw materials, drying/heating and transport. For the processes of drying/heating and transport, GWP can be estimated or measured fairly well. For the extraction/production of the constituent materials however, information is often missing.
- The *use of resources for energy* is also well covered, but the findings are similar to what is found for GWP. This is logical, since the emission of CO_2 is largely due to the combustion of fossil resources for drying, heating and transport. Therefore, there has to be a strong correlation between GWP and the use of resources for energy.
- In the case of bituminous materials, the *resources for materials* which are used over the life cycle are mainly the constituents of the mixture itself. There is of course a significant impact realised by the use of RA and secondary materials. Especially the use of RA is highly beneficial, since it does not only save aggregates from primary sources, but also bitumen.
- *Air pollution* is often studied by emission measurements in the plant or at the worksite. This is a good and objective way of investigating the air pollution associated with the production and construction stages. However, it is very difficult to find information on the air pollution associated with the production/extraction of the input materials or the processing of RA and secondary materials.
- *Health and safety* issues are rarely discussed, probably because it is very complicated and difficult to demonstrate if there are any impacts. Some researchers did measure the exposure of workers to air pollutants, dust and various chemical substances. Results were always below the detection limits.
- The impact on *financial cost* is reasonably well documented, but it will vary depending on many factors, such as the size of the plant, the amount of bituminous mixtures produced and the evolution of the prices of materials and energy over time. The NRA’s need to estimate the cost over the entire life cycle, which also depends on the maintenance needs, the estimated lifetime and a discount rate, used to determine the present value of future cash expenditure. This requires additional information which is not always available.
- It is usually claimed that *recyclability* will not be affected by the material/technology used. However, one has to be extremely cautious with the use of some additives which may cause future health risks when recycling takes place at the end of life. But even if there are no health risks, there may be several levels of recyclablility,

depending on criteria like cold or hot recyclability, the possible recycling rates, downgrading of the RA, … Recyclability is never discussed in such depth.

- *Performance* is well covered for many techniques, thanks to the performance based test methods that are now standard in Europe (wheel tracking tests, water sensitivity, fatigue, …). The fact that the use of RA is possible without a loss of performance is generally accepted, but one should remain alert that this requires a correct mix design and handling/storage procedures for the RA, in order to control the risks and uncertainties associated with heterogeneity and variability of the RA characteristics. Performance testing by different researchers sometimes lead to contradictory conclusions, but it is difficult to understand why if the test procedures are not described in full detail.

The deliverable report D1.1 was not intended as an exhaustive literature review. There is probably more information to be found and more information will certainly appear in the coming years, since sustainability issues are gaining more attention day by day. However, production of this deliverable has proved very useful in terms of framing the future work planned in the EDGAR project:

- This deliverable D1.1 has provided a good overview of current knowledge and knowledge gaps, but it was recognized that the information remains very general and the reliability is often variable. One of the biggest problems is that the boundaries of the system to which the data apply are not always well defined. In that case, it is very difficult to interprete or compare data. It is clear that, for the following work packages of EDGAR, the project team will have to dig deeper to find more detailed and reliable data, or methodologies that can be utilised to provide reliable data.
- The criteria on which the methodology in WP2 will be based shall not be too detailed, since the literature shows that it would be very hard for NRA's to fill in all the required detailed information. This relates to a similar conclusion made in deliverable D2.1 regarding the number of sustainability criteria.
- The report forms a good basis for the selection of the test cases that will be considered in WP3. It is already clear that the use of RA shall be among the most important test cases, since the benefits of this technique are apparent for each criterion that was considered, especially for GWP, use of energy and material resources and financial costs.

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List of abbreviations

APA: Asphalt Pavement Analyser
AWD: Asphalt Workability Device
BEES: Building for Environmental and Economic Sustainability
CIR: Cold In-place Recycling
ECHA: European Chemical Agency
ECI: Environmental Cost Indicator
EE: Energy Equivalent
EOL: End of Life
EVA: Ethylene Vinyl Acetate
FHWA: Federal Highway Administration
GHG: Greenhouse Gas
GWP: Global Warming Potential
HMA: Hot Mix Asphalt
HWTD: Hamburg Wheel Tracking Device
HWMA: Half Warm Mix Asphalt
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
MSDS: Material Safety Data Sheet
MSM: Manufactured Shingle Modifier
NMGOC: Non-Methanic Gaseous Organic Compounds
PAH: Polycyclic Aromatic Hydrocarbon
PMB: Polymer Modified Bitumen
POCP: Photochemical Ozone Creation Potential
RA: Recycled Asphalt
REACH: Registration, Evaluation, Authorization and restriction of Chemicals
RRT: Reduced Roofing Felt
RTFO: Rolling Thin-Film Oven
SBS: Styrene Butadiene Styrene
SMA: Stone Mastic Asphalt
TVOC: Total Volatile Organic Compounds
VOC: Volatile Organic Compounds
WMA: Warm Mix Asphalt

Annex 1: List of criteria and associated life stages

Assessment	criterium	quantified by	Production	Construction	Use	EOL	benefits
Planet (environmental aspects)	global warming potential	kg CO2e (<CO2,CH4,N2O)	x	x	x	x	x
	ozone depletion	kg CFC11e	x	x	x	x	x
	acidification of soil & water	kg SO2e	x	x	x	x	x
	eutrophication (water fresh&marine and terrestrial)	kg PO4e	x	x	x	x	x
	photochemical ozone creation (smog)	kg ethene e	x	x	x	x	x
	depletion of abiotic resources (non fossil elements)	kg Sb e	x	x	x	x	x
	depletion of abiotic resources (fossil fuels)	MJ, net calorific value	x	x	x	x	x
	hazardous waste disposal	kg				x	
	non hazardous waste disposal	kg				x	
	renewable primary energy use	MJ	x	x	x		
	renewable raw materials use	MJ	x		x		
	non-renewable primary energy use	MJ	x	x	x		
	non-renewable raw materials use	MJ	x		x		
	resource depletion - water use	m3	x		x	x	
	eco toxicity (water)	1,4DB	x	x	x	x	x
	eco toxicity (soil)	1,4DB	x	x	x	x	x
	eco toxicity (human)	1,4DB	x	x	x	x	x
	air pollution	PM10, NO2	x	x	x	x	x
eco-efficient	materials for recycling	kg					x
	use of secondary materials	kg	x		x		
	materials for energy recovery	kg					x
	downcycling/upcycling	kg					x
	compatibility recycled materials; no detrimental effects						x
socio-environmental	conserve or improve aesthetic character of environment	qualitative	x	x	x		
Profit/prosperity (economical aspects)	annualised life stages (till installation) cost	€/year	x	x			
	annualised life cycle cost	€/year	x	x	x	x	x
	construction risks and uncertainties	qualitative		x	x		
	maintenance costs	€/year; road performance indicators (indirect)			x		
	recycling costs	€					x
People (social aspects)	construction nuisance for residents	qualitative		x	x		
	health & safety for road workers	incidents; qualitative		x	x	x	
	health & safety for road users	incidents; spoorvorming, textuur, APL, stroefheid			x		
	communication with asset users	qualitative		x	x		
	controlled source materials	qualitative	x				
	integration in surroundings	qualitative	x				
	acoustic surface characteristics	dBA			x		
	vibrations for local residents	(peak) accelerations		x	x		
socio-economic	reducing construction time	days+€		x	x		
	reducing maintenance time and frequency	days+€			x		